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A CLASSIFICATION OF THE FACTORS WHICH CAUSE FLOODING IN WESTERN CANADA

by

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For Annemarie,

Patience

Persistence

Encouragement

&

Support

Thank-you

ABSTRACT

In Canada, the United States and many other countries, frequency analysis of streamflow data for the period of record is often used in flood prediction with little or no review of supplemental materials. Those involved in flood damage reduction research and planning use the calculated frequencies when making important flood management decisions. Flood frequency analysis, however, is essentially based on the existing streamflow records, which in Canada are often less than twenty years in length. Using an extensive literature review, the author demonstrates that it is not necessarily correct that each potential combination of the factors which can cause flooding, and/or contribute to variations in flood intensities, has occurred during this short period. We have additional information on these factors which can cause flooding and this thesis is, in part, an attempt to identify and classify these factors and suggest in an initial way the frequency patterns for some of them.

The objective of the author in this study is to develop this information source which will supplement existing flood forecasting methods (flood frequency analysis) thereby providing planners with a better foundation when making flood damage reduction decisions. To this end, the author has developed a classification of a wide range of the factors which can cause and/or contribute to flooding in Western Canada. Information derived from published literature and solicited from government sources and private researchers in related disciplines has been used to identify the flood causal factors presented in the classification. The classification is divided into nine sections with related subsections in each, and both natural and man-influenced flood causal factors are included. A more detailed discussion concerning relevant information, occurrence patterns and management alternatives for many of the flood causal factors follows the classification. The author has included maps within the text which are an initial attempt to map the distribution patterns for the better documented flood causal factors.

Flood frequency analysis will continue to be our major tool

of flood prediction and forecasting, but the hazards and damage in flood prone areas will continue to grow despite the use of better data bases. With supplemental information on causal factors, planners may be able to reduce these impacts because there will be fewer unexpected events and they will have a better understanding of the changing patterns present.

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Special thanks to Mr. Gerry Davis of the Edmonton Department of Water and Sanitation for proof-reading this thesis and providing many suggestions which proved to be very helpful including that

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CHAPTER ONE: INTRODUCTION

1.1 Problem Statement:

If flood patterns in Western Canada could be attributed to a single cause, forecasting and management planning would be relatively simple.* There are, however, many factors which cause and contribute to flooding, and flood variations are major. If we are to better understand these patterns and provide more efficient forecasting, and an appropriate range of management alternatives, it is necessary for us to have a better appreciation of the factors which can cause or contribute to flooding. Many of the people involved in flood forecasting and/or prediction will develop perspectives concerning causal factors and in time will gain intuitive experience concerning what to expect and why for specific regions. Their experience may include a wide range of flood causing factors, yet if other factors are responsible for a rare and unexpected flood event or magnitude they may be caught unawares. Similarly, they may not fully appreciate the maximum possible effect of known factors. It is the purpose of this research to develop a classification of a wide range of causal and contributing factors and provide some indication of the role of each in flooding in Western Canada. It is hoped that this information will supplement existing flood forecasting methods such as flood frequency analysis and contribute to a better understanding of the factors which can cause and/or contribute to flooding. By further expanding the information base such a classification will contribute to a more solid foundation for planning and decision making.

The author is not implying that those involved in flood damage reduction in Western Canada are not taking steps to control flooding. On the contrary, this classification would simply be a tool for the planner so that he could be better aware of the flood causal

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* Throughout this research the term "forecasting" will have a broader meaning in that it will also mean prediction.

factors which are present in his district. It would also enable him to understand why present and future flooding need not follow all of the patterns of the past if there have been, and will be, changes in these factors in the future. For example, in the province of British Columbia logging has drastically changed the runoff regime in many watersheds over very short periods of time. Varying circumstances such as lower or higher than average precipitation values during the period of logging may cause anomalies in the streamflow records. With a better appreciation of the potential impacts associated with logging in a particular region the planner would be able to make more informed management decisions before and after logging occurred.

1.2 The Flood Problem:

Flooding has plagued the inhabitants of Western Canada since the first settlements were established in the late 1700's (the term "flooding" describes all instances when the channel capacity is exceeded and water flows onto the flood plain). Despite the flood hazards, however, the need for good access to transportation routes, water supplies and fertile land prompted the early settlers to locate adjacent to the rivers and lakes. While a small proportion of the settlers learned to locate away from these often hazardous locations, many of the early settlements were developed in flood prone areas. Often these have grown to the present urban centers, flood hazard intact. For example, in 1875 early settlers and the Northwest Mounted Police established Fort Calgary at the confluence of the Bow and Elbow Rivers where several major floods were later experienced. As the City of Calgary expanded, rapid development continued on the flood plain and the potential for a severe flood remains (Calgary's flood situation will be further examined in Chapter III).

There are many examples of serious and costly floods in Western Canada which possibly could have been reduced in their severity had proper flood management measures been implemented. The 1948 Fraser River flood cost the provincial (British Columbia) and federal governments approximately $22 million (1948 dollars) in compensation

payments and forced the evacuation of over 16,000 people (Fraser River Board, 1963. p.56). The Red River flood of 1950 was perhaps the worst flood ever to have occurred in Western Canada. Damage was in excess of $30 million (1950 dollars), but it has been estimated that the true cost may actually have exceeded $100 million (Rannie, 1980. p.211). In all, 10,500 homes were flooded along the Red River and 100,000 people were evacuated. In 1979, the Red River flooded once again, but an elaborate system of flood control works helped reduce the flood damage to approximately $30 million (1979 dollars), and only 7000 people were evacuated even though the flood levels were just below those of the 1950 flood. In each of these examples a better understanding of the relevant flood causal factors would have assisted planners to adjust their management practices more efficiently and hence reduce the flood problems. In reference to the Red River flood problem, a better understanding of the factors which cause and contribute to flooding may result in a broadening of the potential range of flood damage reduction alternatives. These alternatives might include upstream storage, controlled drainage, flood proofing and other measures.

Flooding in Western Canada occurs as a result of both natural and human influences. Rapid urbanization and industrialization in many areas of Canada have altered the natural drainage regimen, often increasing the flood hazard. Increased runoff resulting from man's activities, such as changes in the infiltration and storage capacities of agricultural land, the formation of impervious urban surfaces, urban infringement on the flood plain and land clearing in watershed areas, are among the many factors which can contribute to greater flood peaks.

1.3 Objectives and Procedure:

It is the author's contention that the development of a comprehensive classification of the factors which cause flooding will help us to improve our flood forecasting and management analyses. Flood frequency analysis (based on recorded streamflow data) is currently the principle method of flood forecasting in use, and consequently,

is used as the basis for many flood management decisions. Many planners, however, when presented with a flood frequency estimate do not have a good appreciation of the method used to calculate the estimate and, consequently, do not recognize the limitations associated with that method. The flood estimate may be statistically correct relative to the data base, but the confidence afforded that value by the hydrologist (who calculated it) and the planner (who employs it) may vary greatly. It will undoubtably take many years before both the statistical methods and period of record are sufficiently developed so that reliable flood estimates can be consistently determined. Assuming that these methods will be better developed, there are no guarantees that the causal factors will remain unchanged. We must, therefore, develop other methods which will broaden the data base and supplement existing flood forecasting procedures thus allowing planners to make more informed flood management decisions.

In the work that follows, it is most important to appreciate that the classification is not designed to replace flood frequency analysis, only to supplement it. This research is in part an attempt to introduce a novel concept which will help to broaden the information base and understanding of flood causal factors. The classification provided herein is a framework for further research. Further extensive study and more substantial resources would develop this framework and contribute to this as a more useful component in our ability to predict and forecast flooding.

The following chapters have been designed to progressively illustrate the need for a better appreciation of the flood causal factors by planners and others when using flood frequency estimates as the basis for flood management decision making. In Chapter II, the physiographic elements relating to the topography, climatology and hydrology are reviewed as they pertain to flooding in Western Canada. This chapter provides the reader with a general understanding of the elements which are responsible for the variations in yield and reasons for the types of flooding which can be experienced in the study area.

In Chapter III, a review of the literature concerned with

the technical aspects of flooding, specific flood events, and historical flood surveys will make apparent the limited acknowledgement by researchers of the many factors which can cause floods. Some limitations in current flood frequency analysis techniques will also be examined including the hazards and short-comings of using the period of record as the sole source of data. The draw-backs of not acknowledging the influences of many flood causal factors on flood flows or of acknowledging only a select few causal factors will be presented. Prior attempts to classify the causes of flooding will also be reviewed.

The classification of the causes of flooding will be presented in Chapter IV. The identification of the flood causal factors in the classification is based on information derived from published literature and solicited from government officers. A review of the individual flood causal factors with detailed descriptions and examples will follow the classification. For the more commonly experienced causal factors, various management alternatives will be discussed. Generally mapped distribution patterns for many of the better documented factors are also provided. It should be noted, however, that there are many gaps in the data required for the completion of these maps. If these initial maps are useful (as is anticipated), further studies and mapping programs may result in better defined patterns.

In Chapter V, the conclusions and recommendations will be presented. It should also be noted that in Appendix II, a glossary of terms relevant to this study is presented.

1.4 Study Area Selection:

The selection of a study area is crucial in most scientific research, and for this reason a variety of alternatives was considered. It became apparent from the nature of this research that the size of the study area was an important factor. A region such as Alberta was found to be unsuitable as neither the range nor the contrasts of flood causal factors was great enough for the development of a broad classification. A classification for this area would have been too limited and difficult to apply to other areas. To maintain a study region of manageable proportions, it was determined that

an area the size of Canada would be impractical and not enough additional contrast was indicated. It was, therefore, decided that Western Canada, including British Columbia, Alberta, Saskatchewan, Manitoba and the mainland of the Yukon and Northwest Territories, was an appropriate choice. In Figure 1.1, the major political boundaries and urban centers related to this study are mapped. In this region there is a wide variety of flood causal factors present and we have access to a good range of the necessary data and descriptive illustrations. It is recognized that some flood situations are missing in the study area (e.g. from hurricanes), but a sufficient number of causal variables are present for useful descriptions, analyses, and classification.

Figure 1.1 WESTERN CANADA: POLITICAL BOUNDARIES AND URBAN CENTERS

CHAPTER TWO: THE SETTING - WESTERN CANADA

2.1 Introduction:

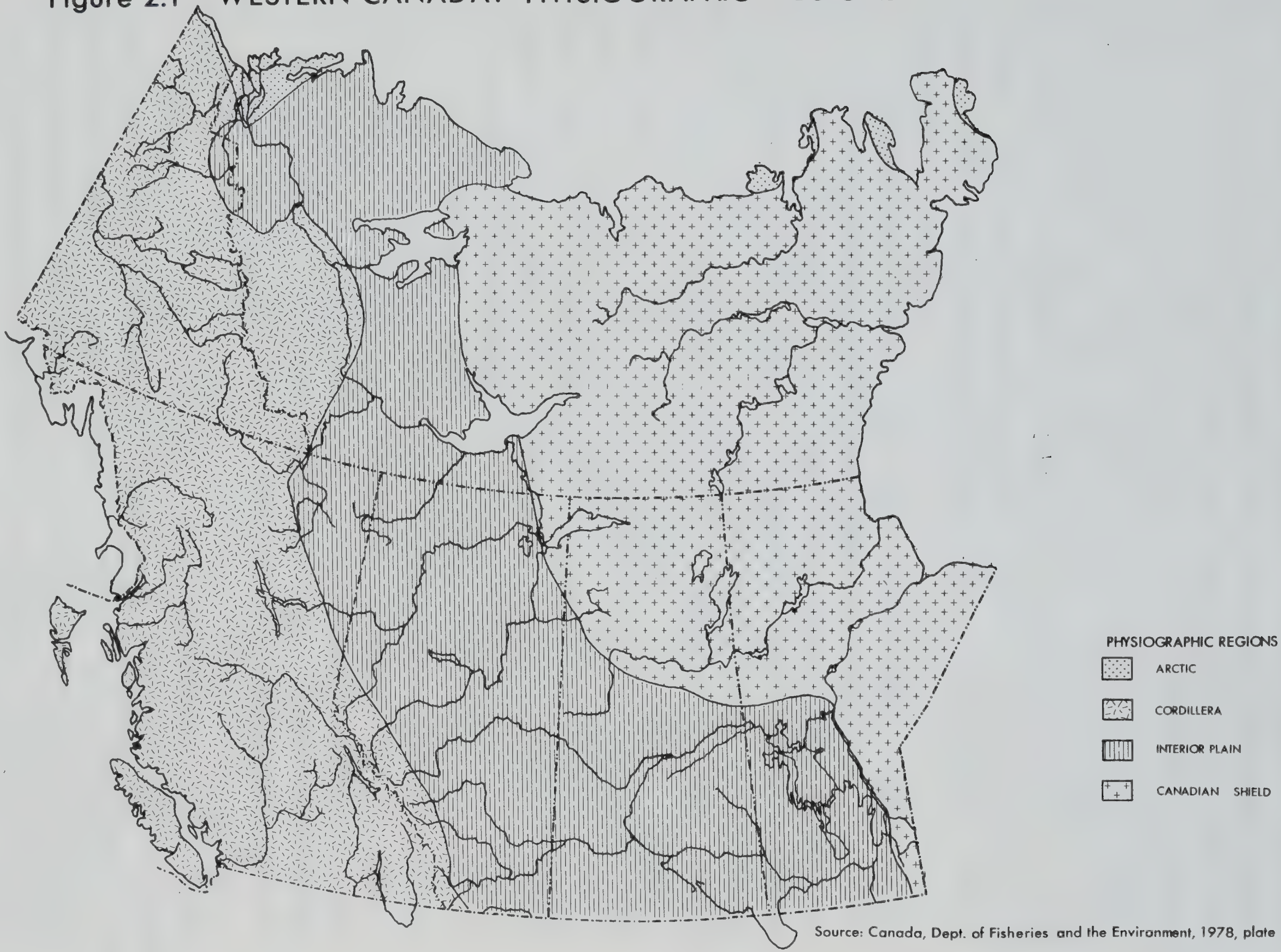
Western Canada is a vast region of widely varying topographic, climatic, geologic, hydrologic, vegetative and soil characteristics. While all of these variables contribute to flooding in varying degrees, a discussion which fully describes the patterns of each would extend beyond the requirements and scope of this thesis. It is the author's intent, therefore, to generally outline the more important elements (hydrologic, topographic, climatologic) as they pertain to flooding in Western Canada. An examination of these elements should help in outlining the runoff charactersitics of the different geographical regions present in the study area. It will also serve as a background for the discussion of the flood causal factors which will be presented in Chapter IV.

2.2 Relief of Western Canada:

Putnam and Putnam (1970, p.15) and Environment Canada (1978, plate 20) have identified four different physiographic regions in Western Canada; the Cordillera, Interior Plains, Canadian Shield (including the Hudson Bay Lowlands) and the Arctic (Figure 2.1). They suggest that while these regional divisions are very general, major differences in the underlying rock structures and in the patterns of surface features make such physiographic divisions possible. It is important to note that these regions extend beyond Western Canada into the United States and into eastern and northern Canada.

The Cordillera is a geologically complex region, and includes most of British Columbia, the Yukon Territory and part of Alberta (Figure 2.1). The area is predominantly mountainous and is underlain by crystalline and steeply folded sedimentary rocks. A major plateau runs the length of the Cordillera's interior and is underlain by volcanic and sedimentary rocks in many areas. Along the west coast, the Pacific Coast Mountains provide the lower, central interior

Figure 2.1 WESTERN CANADA: PHYSIOGRAPHIC REGIONS



Source: Canada, Dept. of Fisheries and the Environment, 1978, plate 20.

with a shield from the moist Pacific air. In the eastern Cordillera, the MacKenzie and Rocky Mountain Ranges dominate. Environment Canada (1978, plate 20) suggests that the rivers in the Cordillera are structurally guided by the mountains, and a rectangular drainage pattern is dominant (other patterns are present on a local basis). The major rivers in this region (Fraser, Yukon, Columbia, Liard) all follow the orientation of the structural valleys in much of their courses. In the Cordillera, many of the lowlands have alluvial landforms such as fans, flood plains, and deltas. These regions can be particularly prone to flooding.

The Interior Plains region lies immediately to the east of the Cordillera (Figure 2.1). This region extends from the Canada-U.S. border northward to the Arctic Ocean and encompasses the west-central portion of the Northwest Territories, the northeastern quadrant of British Columbia, most of Alberta, the southern half of Saskatchewan and southwestern Manitoba. With the exception of a folded belt of sedimentary rocks along the western border, the Interior Plains are generally underlain by Cretaceous and Tertiary sedimentary rocks which dip gently toward the southwest, away from the Canadian Shield (Laycock, 1972, p.6). The rivers are usually incised through the mantle of glacial deposits and into bedrock. The Interior Plain has two predominant drainage directions; northward to the Arctic Ocean via the Mackenzie River, and eastward from the Rocky Mountains toward Hudson Bay via the Saskatchewan and Nelson Rivers. Also present in southern Alberta and Saskatchewan is the Milk River which eventually flows into the Gulf of Mexico. These drainage networks are outlined in Figure 2.1 and their characteristics are discussed later in this chapter.

Many upland areas are present in the Interior Plains region. The more prominent of these are the Cypress Hills, Caribou Mountains and Swan Hills in Alberta; Porcupine Mountain in Saskatchewan; and Riding Mountain in Manitoba. These upland areas are not particularly high, ranging between 250-800 metres above the surrounding plains. In the southern portion of the Interior Plains the land rises in elevation from east to west in what has been described as a three

step sequence. The first step is the Manitoba lowland which lies below the Manitoba escarpment, the second rises to the Missouri Coteau and the third step continues upwards to the foothills. Laycock (1972, p.6), however, feels that the three step concept is overly simplistic and that there is little indication of this pattern in the north and many areas of the southern prairies. It is this gradient change, in part, which causes many of the southern prairie rivers to become entrenched into the bedrock and to flow eastward toward Hudson Bay. It should be noted that many gradient changes have also resulted from recent glaciation and many streams flowing from uplands have developed fans, flood plains and deltas in the adjoining flatter lowlands(e.g. lacustrine plains).

Most of the remaining area in Western Canada is part of the Canadian Shield region (Figure 2.1). This physiographic region generally consists of massive, ancient crystalline rocks (gneisses and granites) with a local relief of about 100 metres. Despite this low surface relief the area is difficult to traverse as the last glaciation left a badly scoured and poorly drained surface. Grey (1978) states that the drainage patterns vary widely and have not developed significantly since the last glaciation. The main streams generally follow the slope of the land, creating radial patterns from the central Kazan Plateau area in the District of Keewatin. The heavily fractured and jointed surface of the Shield also influences drainage. Flashy flow from bare-rock areas often floods lowland areas, many of which have organic terrain (muskegs) and inadequate drainage in some seasons. In general, however, the southern and northeast areas of the Canadian Shield drain into Hudson Bay and water in the northwestern portion and the area surrounding Lake Athabasca in northern Saskatchewan flows off the plateau toward the Arctic Ocean.

The Hudson Bay Lowlands, which lie in the northeastern quadrant of Manitoba from roughly Churchill to the Ontario border (and beyond), are considered to be part of the Canadian Shield region (Department of Energy, Mines and Resources and Information Canada, 1974; Grey 1978, plate 20; Putnam and Putnam, 1970). The Lowlands are an area of sedimentary flat bedded or very gently dipping rock within the

Shield, and there is very little local relief. Consequently, the surface drainage is poorly developed and is adequate only in the vicinity of rivers (e.g. Churchill and Nelson Rivers) which pass through this area to Hudson Bay (Zoltai, 1973, p.18). Grey (1978, plate 20) states further that the drainage in the lowlands generally follows the slope of the land and is mainly dendritic with some structural modifications.

The last and smallest of the four physiographic regions in Western Canada is the Artic region. There are, however, only a very few areas where this region extends into the study area (Figure 2.1). These areas are generally underlain by flat sedimentary rock and the local relief is very low. The drainage in these low-lying areas is relatively poor and disorganized. The continental Arctic region is basically a continuation of the Interior Plain physiographic region. It is in the northern islands in the District of Franklin, that the characteristics of the Arctic physiographic region are most apparent (Fisheries and Environment Canada, 1978, plate 20).

2.3 Climate of Western Canada:

In hydrologic research it is recognized that there are close relationships between the climatic elements present in an area and the potential for flooding. The diversity of topography and climate in Western Canada can result in different types of flooding in different regions at different times. For example, on the southern coast of British Columbia, the warming influence of the Pacific Ocean produces moderate winter air temperatures which can cause winter precipitation to fall as rain in low-lying areas. During December 1979, 1980, 1981 and 1982 mid-winter rainfalls of this origin (in combination with other factors such as snowmelt) contributed to extensive flooding in the southwest portion of the province. Winter flooding of this type, however, is much less likely to occur in Winnipeg where arctic air masses dominate during most of the winter. In the Winnipeg area, precipitation flooding usually occurs during the spring when moist maritime tropical (mT) and maritime polar (mP) air masses are present.

A complete analysis of the climate of Western Canada would

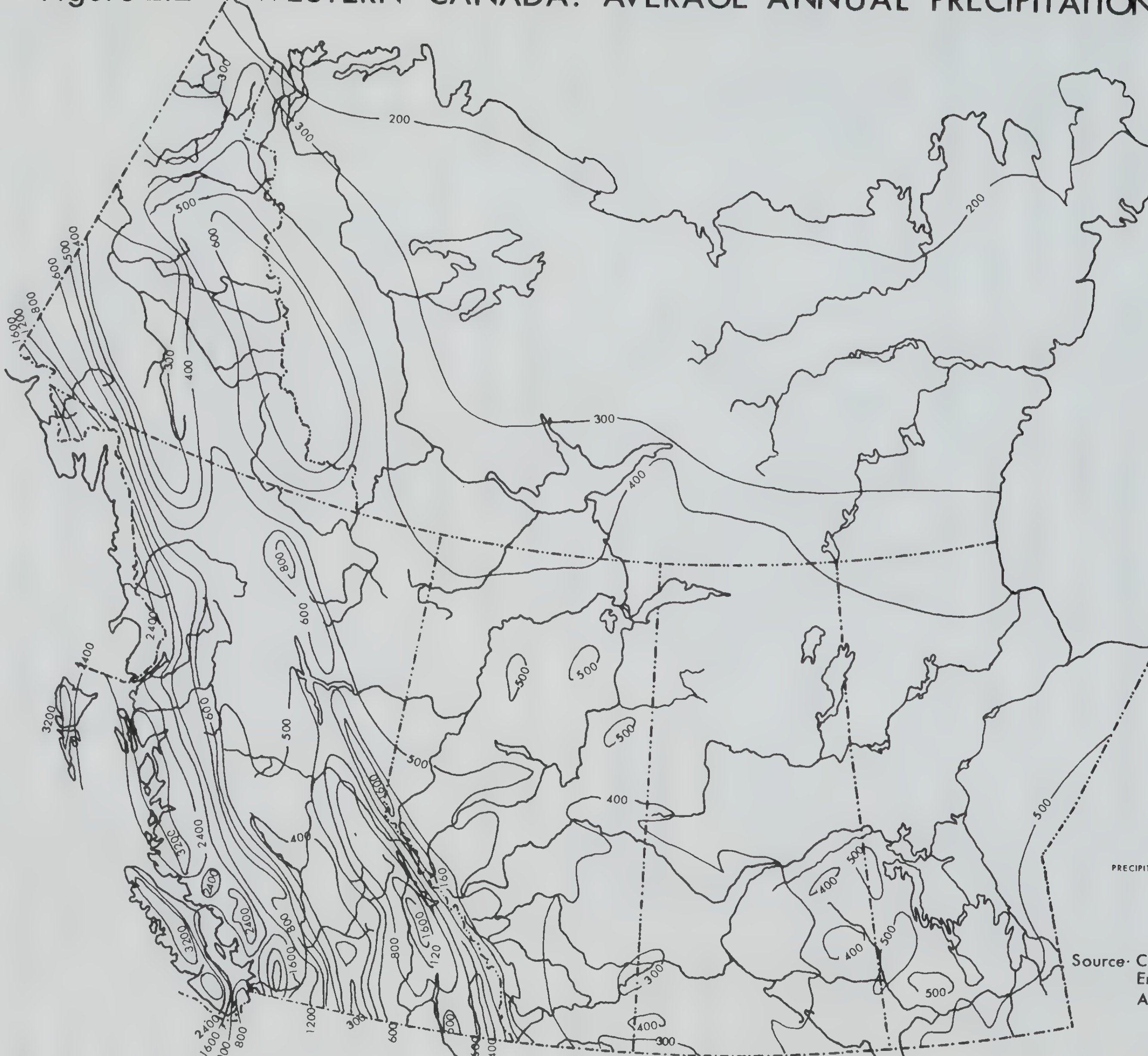
require data for many climatic elements (air temperature, air pressure, wind, precipitation, solar radiation, etc.). The following discussion, therefore, will be focussed upon the precipitation and air temperature patterns in Western Canada as these climatic elements are most often associated with flooding (Hare and Thomas, 1974; Longley, 1972; Thomas, 1953). Other climatic factors which influence flooding will be noted only where related to precipitation and temperature.

2.3.1 Precipitation:

Throughout Western Canada the level of precipitation varies widely. Figure 2.2 is an illustration of the mean annual precipitation distribution in the study area in the period 1921 to 1974 (Energy, Mines and Resources Canada,1974; Environment Canada, 1978, plate 3; Laycock, 1976). While it appears that the precipitation patterns in Figure 2.2 are quite complex, general relationships do exist. The most striking feature is the abundance of precipitation along the coast of British Columbia and in the southwest corner of the Yukon Territory where, in certain areas, over 3200 mm of precipitation can fall annually. This heavy precipitation is usually caused by two events; orographic uplifting and cyclonic storms. Very moist mP air carried landward from the Pacific by the prevailing wind is forced upward by the coastal mountain ranges and orographic precipitation results. Prolonged, and sometimes heavy rainfall can also occur when a Pacific cyclone approaches the west coast. The majority of the coastal precipitation occurs during the winter, but in the lower elevations rainfall greatly exceeds the amount of precipitation received as snow. This precipitation cycle is clearly illustrated by the mean seasonal runoff pattern of the Sooke River on Vancouver Island (Appendix I -C). Here the majority of the runoff occurs during the winter months and there is low flow during June, July and August.

Winter rainfall along the Pacific coast often causes severe flooding in many of British Columbia's urban centers. The floods of December 1979, for example, occurred when in excess of 100 mm of rain was recorded during a 24 hour period in many lower mainland centers. Many small creeks flooded and there was widespread flooding

Figure 2.2 WESTERN CANADA: AVERAGE ANNUAL PRECIPITATION



Source· Canada, Dept. of Fisheries and the Environment, 1978, plate 3.
A. H. Laycock, 1976

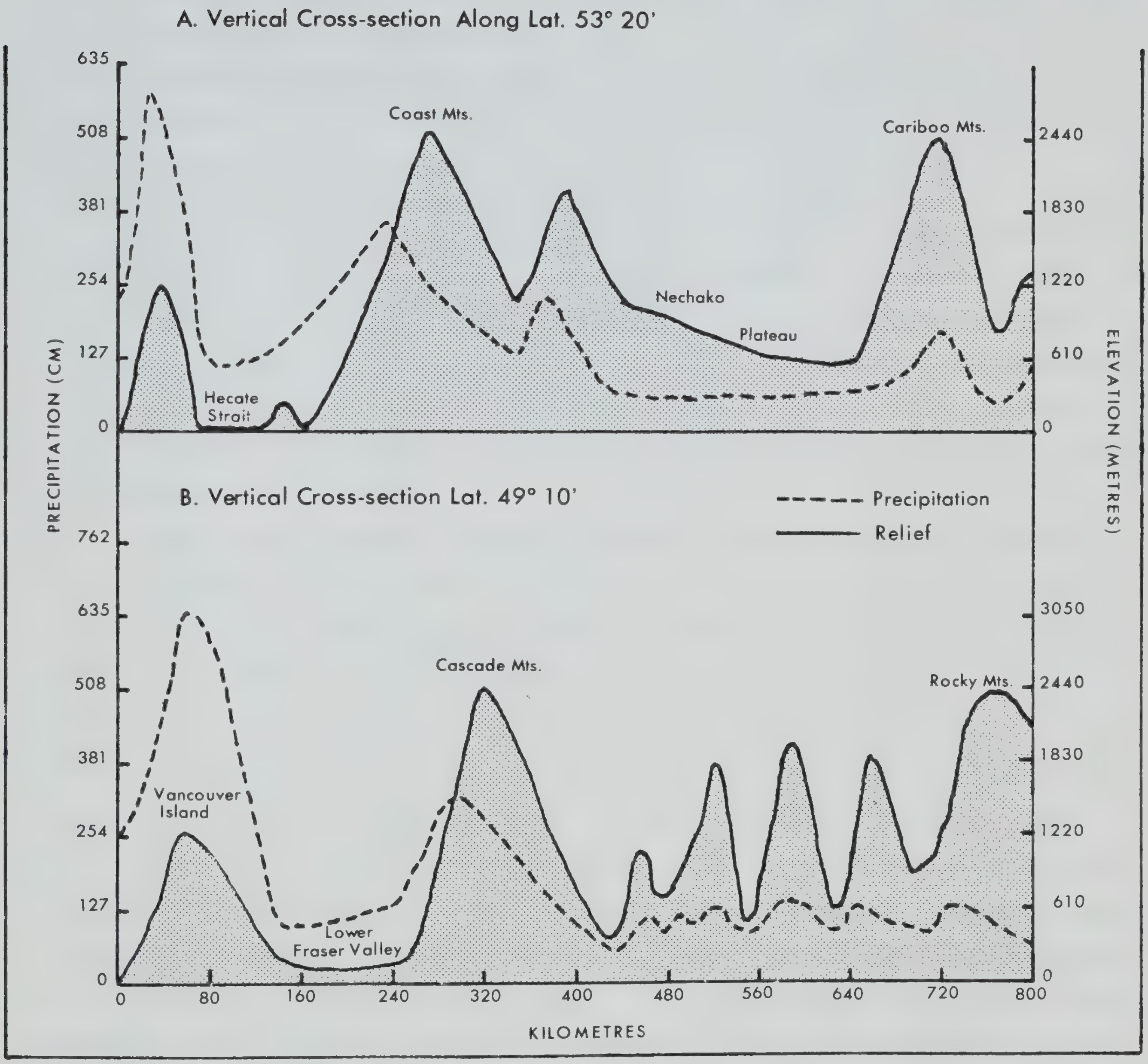
in the low-lying areas of the Fraser River Delta just east of Vancouver. Flooding from winter rains has also occurred frequently further north along the British Columbia coast at Terrace and other communities.

There is one notable exception to this high precipitation regime along the coast of British Columbia. The Gulf Islands, Victoria, and certain areas of the Lower Mainland lie in the rain-shadow of the Olympic Mountains in Washington State and the Vancouver Island ranges (Figure 2.2). The mean annual precipitation experienced in this area ranges from 700-1000 mm per year. In Figure 2.3, this low precipitation region on Vancouver Island is clearly indicated (2.3 B). Also apparent in Figure 2.3 are further relationships between topography and precipitation in southern British Columbia.

In contrast to the high annual precipitation experienced on the western slopes of the coastal range, the eastern slopes and interior plateau are considerably drier (Figures 2.2 and 2.3). After crossing the coastal range the air flows downslope and is heated by compression (adiabatic heating) which causes the evaporation of cloud and a reduction in precipitation (Fisheries and Environment Canada, 1978, plate 3). While there is a certain degree of carry-over precipitation on the leeward summits, large areas of the leeward slopes and plateau between Dawson (Y.T.) and Penticton (B.C.) receive less than 400 mm annually. The mountains and upland regions of the interior plateau receive considerably more precipitation, but the absence of meteorological stations in many of these areas limits the amount of available data. Similarly, in many northern regions of Western Canada climatological stations are limited in number. Therefore, many of the precipitation isolines in Figure 2.2 are not completely representative of the mountainous and northern regions.

In the northern areas of the interior, snowfall can be significant ranging from approximately 200 cm at Prince George to well over 400 cm at Cassiar in north-central British Columbia (these figures indicate the snow depth, not the water equivalent). This often heavy snowpack contributes significantly to the spring runoff which can lead to substantial flooding in British Columbia and the Yukon Territory. This aspect of flooding will be discussed in detail in Chapter IV.

Figure 2.3 RELATIONSHIP OF TOPOGRAPHY TO PRECIPITATION IN SOUTHERN BRITISH COLUMBIA



Source: D.F.Putnam and R.G.Putnam, 1970, p.313.

Another area of high annual precipitation occurs along the western side of the Rocky Mountains (Figure 2.2). Maritime polar (mP) air masses passing over the Rockies are forced upwards causing orographic precipitation (Figure 2.3). Most of this precipitation occurs during the winter as snow which can contribute significantly large volumes of spring runoff to the Pacific, Arctic and Hudson Bay drainage basins. The potential impact of this snowmelt runoff will be described in Chapter IV.

The particularly dry regions in southern Alberta and Saskatchewan (see Figure 2.2) are largely the result of limited moisture within the maritime polar (mP) air mass. As was indicated earlier, most of the moisture within this air mass is released over the Cordillera. Precipitation on the southern prairies ranges from under 300 mm up to approximately 400 mm annually, with most of it falling in the spring and summer. This precipitation contributes significantly to high river discharges and can cause flooding. The extent and full causes of flooding in this area will be discussed more fully in Chapter IV.

While not extremely abundant, there is somewhat more precipitation in the northern and eastern portions of the prairies than the south-western portion. Both Longley (1972) and Weber (personal communication, Sept. 12, 1980) have suggested that the local relief pattern on the prairies is partially responsible for this precipitation distribution. The northwest extent of the Canadian Shield and the higher areas of northern Alberta and southern Manitoba receive from 450 mm to 500 mm of precipitation annually. Weber (personal communication, 1980) feels that these areas are more prone to rain generated floods than watersheds of similar size in other areas of the prairies. He reasons that these areas usually receive greater amounts of storm precipitation because of the orographic uplift, and, due to the steeper slopes, less rain water is lost to infiltration and small depression storage. Laycock (personal communication, Nov. 1980) suggests that much of this flooding is not in the upland areas where most of the water surplus originates. It is in the adjoining plains where changes in gradient have resulted in natural flood plain

development and channel capacities are exceeded with widespread flooding.

Substantial precipitation also occurs in the prairie region from several other causes. As was previously explained, the maritime polar (mP) air mass usually releases most of its moisture over the Cordillera. However, cyclonic and convectional uplift of this air mass can release additional moisture in the prairie region. The uplift mechanism is often provided by convectional activity from the differential heating of surfaces and can also be created by a cold frontal uplift of Pacific air and the addition of the heat of condensation. The resulting rainfall can be very intense and can result in localized flooding. These and other uplift mechanisms are discussed in Chapter IV.

In the summer, relatively heavy rains can be experienced on the prairies when warm, moist maritime tropical (mT) air flows northward from the Gulf of Mexico. Although this event is rare in the western portion of the prairies, it often provides a large proportion of southeastern Manitoba's annual precipitation. Laycock (1972, p.16) has suggested that the proportionate distribution of annual rainfall experienced on the prairies from this source can be approximately 50 percent in Winnipeg, 25 percent in Medicine Hat and 10 percent in Edmonton. In Manitoba, it is often rain from this system in combination with snowmelt which has caused many of the floods on the Souris, Red and Assiniboine Rivers. Floods in these basins generated solely by rain are rare, but have occurred in combination with prior moisture storage from heavy snowmelt on the Assiniboine River in 1954 and 1955 and on the Red River in 1950.

In the Northwest Territories the mean annual precipitation is low (Figure 2.2). Much of it occurs as snow, but the potential for many of the flood problems experienced in this region lies in the high precipitation regions of the Cordillera where the Peace, Liard, Nahanni and Athabasca Rivers and other smaller rivers originate. This situation, while not generally a significant flood causal factor in the Northwest Territories, is referred to in Chapter IV, Section 11.a.

2.3.2 Air Temperature:

In Western Canada the air temperature patterns do not influence flooding to the same degree that precipitation does. Seasonal air temperature changes can, however, have a significant effect on many of the factors which cause flooding, including river and lake ice break-up and precipitation and snowmelt patterns.

The west coast of British Columbia is the warmest winter region in Western Canada with a mean January temperature of over 2.5 degrees Celsius. When this information is compared to the precipitation data in Figure 2.2 it is easy to appreciate why the potential for winter flooding exists.

The southern half of Alberta and British Columbia have a warmer average January temperature pattern than the rest of Western Canada. This is caused by the periodic intrusion of warm maritime polar air masses which moderate the dominant, cold continental polar air masses. During January the rest of Western Canada is blanketed by cold, polar air in most winters and warm spells during this period are infrequent.

Warm, early spring temperatures in the southern portion of the study region are often the cause of the most common flood type in the northern portion of Western Canada. Mild Pacific air flows across the southern Prairie regions in late March and early April raising the air temperature above the freezing point. Water from the melting snow and broken ice fills the southern extent of the northward flowing rivers. In the north, however, cold polar air still dominates and the major rivers are ice-bound, blocking the northward flow of water. The river ice constricts the channel and often ice jams occur which cause extensive flooding in the low lying areas. This is a major problem on the Athabasca River where the towns of Whitecourt, Athabasca and Fort McMurray have often been flooded because of ice jams. This is also a problem in the Northwest Territories (Hay River, Fort Simpson, Fort Norman, Fort Good Hope, Aklavik, Fort MacPherson, and Fort Liard), British Columbia (Fort Nelson), and in the Yukon Territory (Dawson, Mayo and Ross River).

Temperature changes in spring also contribute to the flood

potential on the mountain and prairie rivers. All of the major rivers in B.C. and many of the rivers in the prairies have their headwaters in the Cordillera (South and North Saskatchewan drainage systems). In most years, a gradual rise of the freezing level in the free atmosphere causes the snowmelt runoff to proceed slowly from the lower to higher levels, and consequently a moderately regular flow results. If, however, there is a rapid and sudden increase in the vertical air temperature, the snowmelt runoff can occur very rapidly from a number of levels and cause localized flooding. When accompanied by heavy rainfall (discussed in detail in Chapter IV) substantial flooding can be expected on the prairies and in British Columbia.

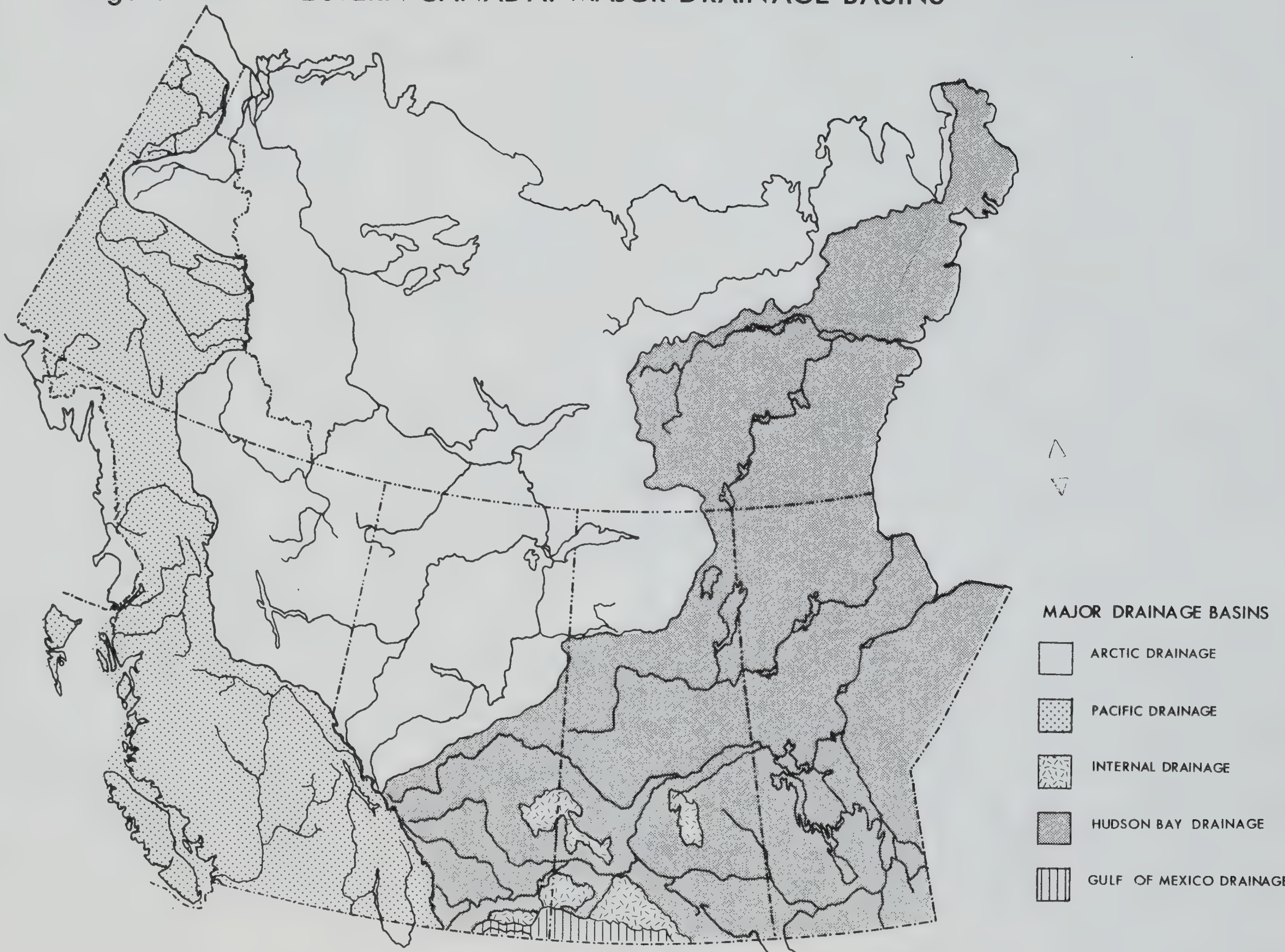
2.4 Hydrology

In Western Canada there are four major drainage systems consisting of small river basins (Figure 2.4). Generally, the Pacific drainage lies to the west, the Arctic drainage to the north, the Hudson Bay drainage to the east, and the Gulf of Mexico drainage is located on part of the southern fringe. Figure 2.4 is a map of the boundaries of the four drainage systems and Figure 2.5 contains the names of the major rivers found in each. Before examining these four drainage systems individually, however, certain water balance patterns in the study region should be appreciated.

2.4.1 Water Yield:

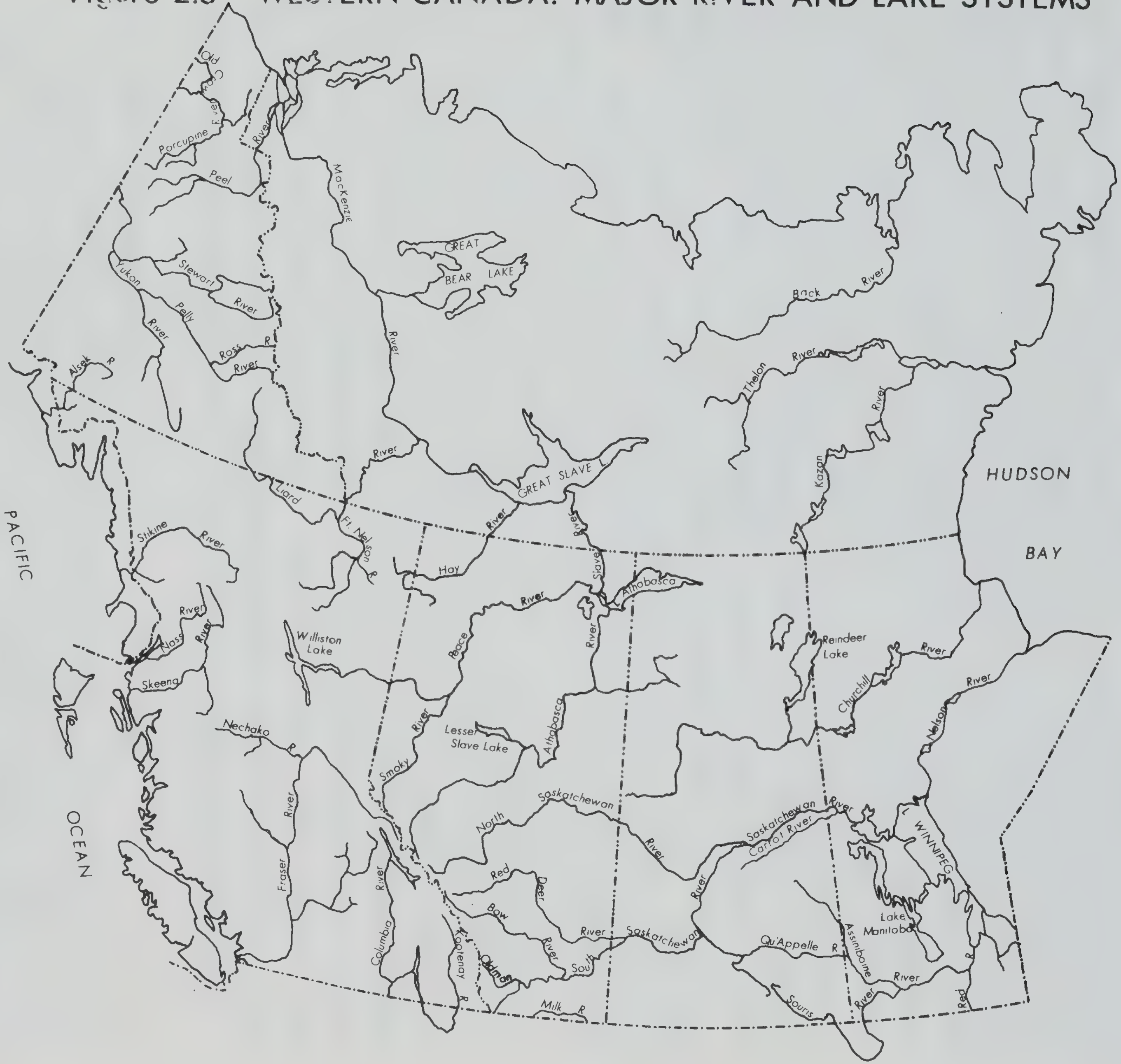
The average annual water yields of Western Canada vary by region due to differences in topography, climate and other variables noted earlier in this chapter. For example, while British Columbia's rivers have an average yield of approximately 31,270 cubic metres per second (m^3/s) over half of this occurs in the coastal regions of the province (Laycock 1976, p.9). Much of this high coastal yield occurs where wet maritime polar (mP) air masses are forced upwards over the coastal mountains of British Columbia (this process was described in the climate section of this chapter). Laycock (1976, p.10) claims that over 30 percent of the streamflow of Canada rises in British Columbia.

Figure 2.4 WESTERN CANADA: MAJOR DRAINAGE BASINS



Source: Canada, Dept. of Fisheries and the Environment, 1978, plate 22.

Figure 2.5 WESTERN CANADA: MAJOR RIVER AND LAKE SYSTEMS



The annual yields experienced in Alberta, Saskatchewan and Manitoba are considerably less than those experienced in British Columbia. Much of the yield (2000 to 3000 m^3/s, i.e., 61 to 93 million cubic decametres per year) originates in the northern portions of the Canadian Shield in upland prairie regions and in the Rocky Mountains (Laycock, 1976 p.9). The southern prairies are relatively dry, and there are many large regions of internal drainage which do not contribute greatly to yield or to streamflow (Figure 2.4). While Figure 2.4 includes the major non-contributing regions there are many other smaller areas of this type which are not shown. Many additional areas have yield in only the wetter years. G.A.D. Green of the Department of Fisheries and Environment Canada (1978, plate 22) suggests that in an average year, well over 50 percent of most southern prairie regions may not contribute to flow. Laycock (1976, p.9) estimates that in large regions of the prairies less than five percent of the annual precipitation enters into streamflow (this figure would be more during a series of wet years).

The total annual yield in the Yukon and Northwest Territories is very high despite the relatively low precipitation experienced in many areas (Figure 2.2). Laycock (1976, p.10) suggests that "the very low potential evaporation plus low infiltration and storage capacities for large areas results in well over two thirds of the precipitation being available for streamflow, but this ranges from less than twenty percent in the warmer southern and southwest lowlands to almost one hundred percent in areas of high elevation and latitude."

2.4.2 Major Drainage Basins:

As is indicated in Figures 2.4 and 2.5, major river systems are located in each of the three largest drainage basins. The largest rivers, however, are located on the northern, western and eastern margins of Western Canada, and many of the smaller rivers are situated on the southern plains. In Table 2.1 the river hierarchy for each major drainage basin is provided. It is interesting to note that in many cases the river systems with the largest drainage areas do not necessarily have the largest mean discharge. For example,

TABLE 2.1

MAJOR DRAINAGE BASINS: AREA AND DISCHARGE

Drainage Basin	Drainage Area (km^2)	Mean Discharge (m^3/s)
Pacific Ocean:		
1. Yukon	275 000	2 360
2. Porcupine	54 100	368
3. Stikine	49 200	1 080
4. Nass	20 700	892
5. Skeena	54 900	1 760
6. Fraser	233 000	3 620
7. Columbia	155 000	2 890
8. Other	228 000	11 100
Arctic Ocean:		
1. MacKenzie	1 787 000	9 910
2. Back	107 000	612
3. Other	1 663 000	5 890
Hudson Bay:		
1. Thelon	142 000	804
2. Kazan	71 500	566
3. Churchill	289 000	1 270
4. Nelson	1 132 000	2 830

Source: Canada. Department of Fisheries and Environment. 1978. Hydrological Atlas of Canada. Ottawa: Ministry of Supply and Services. Plate 22.

in the Pacific drainage, the Yukon River basin has the largest drainage area (275,000 square kilometres), but only the third largest mean discharge (2,360 m^3/s). While not apparent in Table 2.1, this pattern also exists for certain rivers in the Nelson River basin and will be elaborated on later in this section.

The Mackenzie River (9,910 m^3/s) is the largest in Western Canada with the Fraser (3,620 m^3/s), Columbia (2,890 m^3/s), Nelson (2,830 m^3/s), Yukon (2,360 m^3/s), Skeena (1,760 m^3/s), Churchill (1,270 m^3/s), and Stikine (1,080 m^3/s) Rivers following in order (Environment Canada, 1978b. plate 20). Several of the major tributaries of the above rivers (Liard, Peace, Thompson) are comparable in size to the smaller rivers in the above heirarchy. Laycock (1976, pp.11-12) suggests that:

> "in general the mountain streams have the largest and most dependable annual yields, a more favorable regime with a greater ground water base flow, a broader peak flow in spring and early summer and less severe flooding and erosion related to flooding than streams in the foothills and plains. The foothill streams are intermediate in yield and normal regime, but many are subject to flooding and erosion, especially with overgrazing, clearing and burning. The plains streams have low and undependable yields, maximum flow in early spring of most years (and with flooding in late spring and early summer of some years) and relatively poor quality flow."

The following discussion is an elaboration of these general patterns in the major drainage basins in Western Canada.

Arctic Drainage:

The Arctic drainage is the largest of the four major drainage systems in Western Canada (Figure 2.4). It encompasses an area of approximately 3,557,000 square kilometres, including portions of British Columbia, Alberta, Saskatchewan, the Yukon and most of the Northwest Territories. As was stated earlier, the Mackenzie River basin (situated in the Arctic drainage) is the largest in Western Canada. The Mackenzie is "supplied" by a number of large tributaries, including the Liard, Athabasca and Peace Rivers (Figure 2.5). (Specific characteristics of these are listed in Appendix I-A). The headwaters of these major tributaries are located in the mountains in western

Alberta, northeast British Columbia, eastern Yukon and the western Mackenzie District. The seasonal streamflow pattern of these rivers is typical of a mountain, snowmelt regime, experiencing minimum flow during the winter months (January to March), and maximum flow during the late spring and early summer months (particularly in June and July) when warmer temperatures melt the mountain snow and rain falls on the lowlands.

The major northward flowing tributaries of the Mackenzie River are also subject to ice jam flooding during spring break-up. As was previously explained (in the climate section) the southern reaches of many of these tributaries (including the Mackenzie River) are in the southern portion of the basin where warm spring temperatures usually occur first. This can cause the river ice to break-up in the south and flow northward until it meets and jams against the still solid northern river ice. These jams have often caused extensive flooding in many northern urban communities and will be discussed further in Chapter IV.

The eastern part of the Mackenzie River basin has been extensively glaciated and the drainage organization is poor. The many lakes in this region, including Great Bear lake (31,450 square kilometres), Great Slave Lake (28,680 square kilometres, 616 metres deep), and Lake Athabasca (7,966 square kilometres) (Figure 2.5) contribute to modification of the Mackenzie River's flow regime. These lakes provide a more stable flow to the Mackenzie River by acting as large, natural regulatory storage reservoirs.

As Figures 2.4 and 2.5 indicate, the Back River, which drains an area of 107,000 square kilometres, is also located in the Arctic drainage. The northerly location of the Back River basin delays the periods of maximum and minumum monthly discharge as melting occurs later. The maximum mean monthly flow (2,070 m^3/s) occurs in July (Appendix I-A). There are, however, very few inhabitants or urban developments in this region and the extent of the flood hazard is limited.

Hudson Bay Drainage:

The Hudson Bay drainage (Figure 2.4) is the second largest drainage network in Western Canada encompassing most of southern Alberta, Saskatchewan and the District of Keewatin, and all of Manitoba. The Nelson River basin (1,320,000 square kilometres) is the largest drainage basin in the network (Figure 2.5). There are, however, areas of internal drainage located within this basin which are difficult to define because the area involved varies from year to year depending on the annual precipitation and prior ground water and depression storage (Figure 2.4).

The Nelson River is fed by several large tributaries which drain into Lake Winnipeg (Figure 2.6). In the west the Saskatchewan River basin drains an area of 347,000 square kilometres and contributes about 39 percent of the flow in the Nelson River basin (Environment Canada, 1975, p.44). The headwaters of the Saskatchewan River are located in high precipitation regions of the Cordillera (Figure 2.2). Laycock (1957, p.19) states that in dry years 90 percent of the North and South Saskatchewan River's streamflow originates in the Cordillera and foothills which contain only about 15 percent of the total basin area. These high yields are attributed to high precipitation, low potential evaporation and widespread bare rock. During wet years, a much larger percentage of the flow originates on the plains. The tributaries in the Saskatchewan River basin (North Saskatchewan,South Saskatchewan, Red Deer, Bow and Oldman Rivers--Figure 2.5) usually experience minimum monthly average discharges during January and February, and maximum monthly discharges during June and July (Appendix I-B). In many years, the foothill regions experience heavy spring rainfalls which often contribute to high yields and can cause severe flooding.

The Saskatchewan River basin has relatively little natural surface storage. This can be a major determinant of flood occurrence because without adequate surface storage the flow can be "flashy" in nature. This is a problem in southern Alberta and Saskatchewan where there is little natural surface storage on the main streams and tributaries.

While the flow from the Saskatchewan River basin is basically dependable (adequate yearly flow), flow from the Red-Assiniboine River basin is not dependable (inadequate yearly flow) (Appendix I-B). Environment Canada (1975, p.44) reports that this basin which is roughly 260,000 square kilometres in size, only contributes about 8 percent of the annual flow into Lake Winnipeg. It is not unusual for many of the tributaries in this "plains" river basin to experience zero or extremely low flows during the winter months. For example, where the Souris River flows from Saskatchewan into North Dakota, zero flows have been recorded in twenty-one years during the period of record 1930 to 1979 (Appendix I-B). The minimum monthly average discharge during the period of record is only 0.09 m^3/s for the month of January. The maximum monthly average discharge for the same period is 22.5 m^3/s during April. A similar situation exists in the Qu-Appelle River basin and to a lesser extent in the Assiniboine and Red River basins (Appendix I-B). The higher river discharge occurs during snowmelt in March and April and in some years in May and June before soil moisture storage has been greatly depleted.

The Winnipeg River basin, which represents only 13 percent of the Nelson River basin (189,000 square kilometres), contributes approximately 39 percent of the flow entering Lake Winnipeg (Environment Canada, 1975, p.44). The headwaters of the Winnipeg River are situated in the Ontario portion of the Canadian Shield which receives relatively large amounts of precipitation. During April and May, snowmelt and surface runoff from bare rock often result in high yields. During the year the flow in the Winnipeg River is more stable and dependable than that of the plains rivers (Appendix I-B).

It is interesting to note that in Figure 2.1 the physiographic boundary between the Interior Plains and the Canadian Shield runs down the east edge of Lake Winnipeg. To the west of the lake there is very little surface drainage into Lake Winnipeg. Environment Canada (1975, p.44) claims that the surface drainage from the east side of Lake Winnipeg accounts for 14 percent of the total flow into the lake. This is a high yield for the relatively small area involved.

The Nelson River, which flows northeastward from Lake Winnipeg (Figure 2.5) has a very dependable flow with a maximum mean monthly flow of 3030 m^3/s (July) and a minimum mean monthly flow of 1890 m^3/s (February). This dependable winter discharge is maintained by Lakes Winnipegosis, Manitoba and Winnipeg and numerous smaller lakes which act as natural reservoirs and help to regulate the discharge in the Nelson River. The Winnipeg River is the only other river in the Nelson River basin to have a similar regulating system (with Lake of the Woods, Rainy Lake, Lac Seul and others).

The Churchill River basin, located in north central Manitoba and Saskatchewan (Figure 2.5), is the second largest basin in the Hudson Bay drainage (212,000 square kilometres). As was the case for the Nelson and Winnipeg Rivers, the Churchill River is lake-regulated, and has a fairly equable annual flow. Many of the lakes in this basin are either located in the Shield or southwest of the Shield and have been formed by glacial activity. The minimum mean monthly flow during the period of record (1949-1979) above Granville Falls was 730 m^3/s in March and April and the maximum mean monthly flow was 977 m^3/s in July (Appendix I-B). A similar situation exists for the other two large rivers in the Hudson Bay drainage. The Thelon River basin (142,000 square kilometres) and the Kazan River basin (71,500 square kilometres) are both lake regulated, but have a greater variation between maximum and minimum mean monthly discharge than does the Churchill River (Appendix I-B).

Pacific Drainage:

The Pacific drainage system includes the coastal areas of British Columbia and most of the Cordillera region (west of the divide) in both British Columbia and the Yukon (Figure 2.4). While it is the second smallest of the four drainage systems (1,095,000 square kilometres), the Pacific drainage has the largest average discharge (Table 2.1). On the river discharge hierarchy listed previously, the Pacific drainage has the second (Fraser), third (Columbia), fifth (Yukon), and sixth (Skeena) largest rivers in Western Canada (Table 2.1).

The Fraser River basin, which has the highest mean discharge (3,620 m^3/s) in the Pacific drainage, is typical of a mountain, snowmelt regime. The headwaters of the Fraser (and most of its tributaries) are located in the high precipitation regions of the central and southern Cordillera (Figure 2.2 and 2.5). The maximum and minimum mean monthly yields on the Fraser River are 7136 m^3/s (June) and 813 m^3/s (March) respectively (Appendix I-C). This indicates that maximum yields usually occur on the Fraser during spring snowmelt in June. Flooding in the Fraser River basin has occurred in numerous years during the spring snowmelt with the maximum daily discharge on record registering 15,178 m^3/s at Hope in 1948 (the mean discharge is only 3,620 m^3/s). The record minimum daily discharge recorded at Hope was 340 m^3/s in 1916 (Appendix I-C). When this minimum discharge figure is compared to those of the southern plains rivers (Red River 0.03 m^3/s, 1937; Assiniboine River 0.57 m^3/s, 1936; Appendix I-B), the relative reliability of river discharge in the Pacific drainage is apparent.

The Columbia River basin, which drains an area of 154,600 square kilometres in southeastern British Columbia has a mean annual discharge of 2,890 m^3/s (Appendix I-C). The Columbia River basin exhibits the same basic regime and yield characteristics as the Fraser River and a simple comparison can be made between the two basins from the data in Appendix I-C.

The northern river basins (e.g. Yukon and its tributary the Pelly) also exhibit the characteristics associated with a snowmelt, mountain regime. For example, the Yukon River basin, which drains an area of approximately 275,000 square kilometres in the Yukon and northwest British Columbia, has a maximum and minimum mean monthly yield (1945-1979) of 5920 m^3/s (June) and 423 m^3/s (March) respectively. This indicates a high yield during the spring snowmelt and a low yield during late winter just prior to warmer spring temperatures. Most of the southeastern and eastern headwaters of the Yukon and Pelly Rivers are, however, located in areas of lower precipitation than that in the higher mountains to the south and west. Therefore, the annual yields per unit area of the Yukon and Pelly Rivers are

lower than those of the Fraser and Columbia Rivers. For example, the mean annual discharge to area ratio of the Yukon River basin is 2,360 m^3/s per 275,000 square kilometres. In the Fraser River basin this ratio is 3,620 m^3/s per 233,000 square kilometres. Appendix I-C is a listing of some of the basin characteristics for these and the other major river basins in the Pacific drainage.

In the previous discussion on climate it was explained how certain low level regions on Vancouver Island and the Pacific coast received heavy winter precipitation in the form of rainfall. The Cowichan River provides an excellent example of a river basin which experiences maximum runoff during the winter and low yields during the summer. The Cowichan River, which is located on southern Vancouver Island, covers an area of only 596 square kilometres. During the period of record (1913-1979) at Lake Cowichan the maximum mean monthly discharge (92 m^3/s) occurred in December, and the minimum mean monthly discharge (7.3 m^3/s) occurred during September. There are many other rivers in this region which might exhibit these winter runoff characteristics including the Somass River (Appendix I-C).

Gulf of Mexico Drainage:

The Gulf of Mexico drainage includes only a very small portion of Western Canada (29,000 square kilometres in southern Alberta and Saskatchewan) (Figure 2.4). The major river in this southward drainage is the Milk River (Figure 2.5) which drains an area of approximately 6,811 square kilometres. The mean annual discharge for the period of record (1910-1979 at Milk River Townsite) is 186,460 cubic decametres, much of which is the result of transfers from the St. Mary River in Montana. Most of the flood problems have occurred from snowmelt and rainfall on the foothills during May and June. The June 1964 flood event is described in Chapter IV.

The Milk River flow was not very dependable in the years prior to water diversion from the St. Mary River. In nine years during the period of record, the streamflow at the town of Milk River dropped to zero. In past years it has been necessary to divert water from the St. Mary River into the Milk River to supplement flow during

the summer months (Appendix I-D) so that there is sufficient water for irrigation in Montana.

CHAPTER THREE: LITERATURE REVIEW

3.1 Introduction:

During the past thirty years a substantial amount of literature has been published concerning many aspects of flooding. After reviewing much of this literature, however, the author was able to locate only limited references to a classification of the factors which cause flooding. In most of the flood related literature relevant to this study, either the technical characteristics of flooding, the obvious flood causal factors associated with a specific flood event, and/or the flood history of a particular location, are described.

In areas of flood research, such as dam safety and flood plain management, attempts have been made to classify particular flood problems (e.g. Burton 1962, Tada and Ohya 1969, White 1961). Very few attempts have been made to classify flood causal factors, except as a subordinate discussion in papers on specific flood events. Two early and extremely general classifications were those of Russell (1906, pp.198-212) and Barrows (1948, pp.4-7). Russell tried to "classify" the most basic forms of flooding by type (ice jam floods, rain floods, tsunami floods, snowmelt floods, etc.). While Russell's classification was little more than a simple listing exercise, he did recognize that flooding could be caused by a combination of events:

> "Floods depend largely on the topographical features of a country, in combination with sequence of rainfall over its various parts. For any particular river basin the number of combinations capable of producing a flood or high water is large, but the probability of any one of them occurring is small in the case of many rivers. The occurrence of many floods may therefore be considered as due to a combination of favorable circumstances or as purely fortuitous." (Russell, 1906, p.209).

Barrows (1948, pp.4-7) also attempted to develop a classification of flood causes. Like Russell, he was able to identify the principal flood causal factors, but unlike Russell, Barrows attempted to divide the components of his classification into natural and unnatural flood events. Barrows, however, was unable to associate man's influence with natural-type flood causal factors and his classification was not indicative of potential flood events. Had Barrows read what

Russell published forty-two years earlier, he might have designed his classification to be more practical and interrelated, that is;

> "The clearing of forest from land, the extention of cultivation, and the introduction of subsoil drainage, may have some effect on river regime, tending to increase or diminish the highest water stages occurring during floods." (Russell, 1906, p.209).

The limited development of both Russell's and Barrows' flood causal classifications reflect the shortage of flood related information prior to the 1950's. While more information is presently available, however, a detailed classification of the factors that may cause or contribute to flooding has not yet been developed.

The material presented in the following sections of this chapter will illustrate that much of the relevant flood literature is primarily concerned with the technical elements and/or major flood causal factors of a specific event. It is anticipated that a review of this nature will provide a definition of the current state of flood research and a brief indication of the types of material available to those involved with flood damage reduction management. A review of the "state-of-the-art" literature dealing with flood frequency analysis will also be presented.

3.2 The Technical Literature:

In the technical flood literature reviewed, reference to the factors which cause flooding and contribute to variations in flood intensity varied widely. Rodda, Downing and Law (1976, pp.242-245), for example, refer only briefly to snowmelt, rain and dam failures. Similarly, Leopold (1974, p.116) concedes that prior soil moisture storage conditions can have an effect on flooding, but provides no further insights into the effects other flood causal factors such as urbanization and vegetation removal can have on flood intensities.

Many authors have also approached flooding with the attitude that a technical and statistical understanding of flooding will

lead to successful control of this hazard (e.g. Kite 1977, Leopold 1974, Nash and Amorocho 1966, Rodda 1969, Santos 1970). The compendium prepared by Chow (1964), for example, is considered to be one of the better reference works on hydrology. Chow has reviewed most of the complex technical aspects of flooding. Throughout this relatively detailed material, however, there is little reference to any of the numerous flood causal factors. Similarly, Hoyt and Langbein (1955) and Leopold (1974) have only considered the technical characteristics of flooding with passing reference to many of the more apparent causal factors such as rain and snowmelt. Dunne and Leopold (1978) have progressed somewhat further than this. In their recent publication they recognize the contributing effects of certain flood causal factors including dam failure, soil moisture content and urbanization. Much of their research, however, is focussed upon the statistical calculation of the flood hazard and no association has been made between the many factors which can cause floods and the use of flood frequency analyses.

Attempts have been made, however, by a number of researchers to identify more than just the most commonly observed flood causal factors (snowmelt, rain and soil conditions). Ward (1975, p.262) has separated the factors affecting runoff into those factors which combine to influence the total volume of runoff over a period of years, and those which combine to influence the distribution of runoff in time over a period of less than one year. In his first category, Ward identifies the water balance and the physical characteristics (area, altitude, slope, soil and rock type). In his second category, the factors affecting the distribution of runoff in time, Ward identifies meteorological (type of precipitation and rainfall intensity and distribution) and human factors (hydraulic structures, urbanization and agricultural techniques). In his discussions of these factors, however, Ward never adequately develops the idea that these flood causal factors can cause flooding and/or contribute to flood intensities. For example, when discussing the effects of hydraulic structures, Ward (1975, p.272) suggests that the effects of flood peaks are normally reduced by the dam reservoirs, but does

not acknowledge the hazards associated with dams, that is, failure and over-topping. Viessman et al., (1977, p.582) recognize that a potential does exist for dam failures;

> "Critical in the design of a structure such as a dam is the possibility of failure. The sudden release of large volumes of impounded water can create damages even far greater than those experienced prior to construction. Initial heights of retarded water behind the dam, disregarding the total volume of stored water, can produce destructive flood waves for a considerable distance downstream."

To prevent dam failure and over-topping the U.S. Task Force on Spillway Design Floods developed a classification of dams (Viessman, 1977, p.587). In this classification, dams have been categorized into major, intermediate and minor sizes, with the storage, dam height, loss of life, flood damage and spillway design flood indicated for each dam size. For major dams the spillway design flood has been described as "probable maximum; most severe flood considered reasonably possible on the basin," and for intermediate sized dams, it is described as "standard project; based on most severe storm or meteorological conditions considered reasonably characteristic of the specific region." In both categories of dams, the spillway is designed to the potential flood conditions considered most "reasonably" characteristic or possible in the area of location. In certain regions of Western Canada, however, there is a potential for very rare and exotic storms to occur (e.g. intrusion of mT air mass onto the prairies and then rapidly uplifted) which could be outside of the "reasonable" guidelines used to design the dam and spillway structures. It is, therefore, important that planners be aware that there is potential for unusual events of this type in their regions. Similarly, Stolte and Dumontier conducted research on the flood frequencies for mountain and prairie streams in Alberta and Saskatchewan. Within their report they suggest that flooding in this region is caused by snow and/or rain. This assumption is only correct in the broadest terms, and like most of the technical literature, the flood causal factors are only referred to as background for the primary research.

3.3 Specific Flood Literature:

The author was able to locate many references to flood causal factors in the literature discussing specific flood events. Many of these flood reports have reference to only the most obvious flood causal factors, and often, less significant but important factors are ignored. For example, when Chin, Skelton and Guy (1975) analysed the spring 1973 Mississippi River basin flood they examined only the meteorological aspects of the flood as these factors appeared to be the most significant and contributing elements. Similarly, Cooley, Aldridge and Euler (1977) elected to describe only the meteorological elements of the December 1966 Grand Canyon flood in Arizona. In each of these examples there was no reference to any other factors which may have contributed to the flooding, that is, land use changes, urbanization, soil moisture conditions and others.

3.3.1 Rain:

The flood causal factor most commonly discussed in flood reports is rainfall. The degree of inclusion of other causal factors varies by report. The reports of Aldridge (1970), Burkham (1970), Butler and Mundorff (1970), Childers, Meckel and Anderson (1972), Dean (1971), Gilstrap (1972), Roeske, Cooley and Aldridge (1978), Rostvedt (1968a, 1968b, 1970, 1972), and Schroeder (1974) are typical examples of studies with this limitation. Roeske, Cooley and Aldridge (1978), for example, examined the 1970 flood which occurred in the states of Arizona, Utah, Colorado and New Mexico. The only flood causal factor referred to was the record rainfalls which resulted when a mass of moist tropical air from Pacific storm Norma collided with a cold front from the northwest. The influences of other flood causal factors (e.g. land use changes) were not considered.

Rostvedt (1968a, 1968b, 1970, 1972) has compiled a yearly summary of the outstanding floods recorded in the United States for the U.S. Geological Survey. Many of the flood descriptions, however, refer only to the most apparent causes of flooding (usually one or two factors). For example, when reporting on the severe 1963 floods on the western slopes of the Appalachian Mountains from Alabama

to West Virginia and Ohio, Rostvedt (1968b, p.B.1) claims that rainfall from three storm systems caused the flood. Certainly the precipitation from these storms was the primary cause of the flooding (resulting in 26 deaths and approximately $100 million damage), but Rostvedt makes no attempt to identify what other factors may have contributed (e.g. excessive land use changes such as coal mining, forestry, increased urbanization).

The previously cited examples are not the only cases where there has been a limited identification of flood causal factors. Although it would be possible to compile numerous examples of this type, the utility of such research is unclear. Many reports have, however, included limited consideration of the effects of other flood causal factors during heavy rain events. Boner and Stermitz (1967), Henz, Scheetz and Doehring (1976), Matthai (1969), Rostvedt (1968a), and Snipes (1974), have reported on floods in the United States where the principal causal factor was rain, and have also identified other contributing flood causal factors. For example, Matthai, in his 1969 report on the June 1965 floods in the South Platte River basin in Colorado, suggests that the flood producing storms followed a relatively wet period which created saturated soil conditions. The resulting surface runoff was particularly heavy because the soil was unable to retain further moisture. Matthai (1969, p.12) further states that the snowmelt runoff was a contributing but not significant factor during the flood. An important observation contained in Matthai's report was that "through Denver and its suburbs the amount of overbank flow along the South Platte River was aggravated by plugged bridges; and the depth was increased by encroachments on the flood plain." This statement clearly indicates the potential influence of engineered structures on flood flows, and yet this was one of the few references to the potential repercussions of man's activities in the flood reports reviewed.

Despite an earlier example, J.O. Rostvedt of the U.S. Geological Survey has occasionally attempted to identify more than one causal factor when reporting certain flood events. Rostvedt (1968a, p.1) suggests that the 1962 floods in Idaho and adjacent areas of Nevada

and Utah resulted from;

> "a combination of prolonged low-intensity rainfall, moderate amounts of snow on low-altitude areas, a period of high temperature, and a glaze of ice over deeply frozen ground."

Other researchers in the United States have also reported on many of the most basic flood causal factors. When reporting on the 1976 Big Thompson flood in Colorado, Henz, Scheetz and Doehring (1976, p.284) explain that heavy precipitation (caused by a convergence of warm moist air from the Gulf of Mexico and cold air from Canada) combined with soils which had a limited surface storage capacity and steep slopes were the main causes of the flood. Snipes (1974, p.1) reports that the June 1965 floods in the Arkansas River basin were caused by the combined effects of heavy rainfall, snowmelt runoff and saturated soil conditions. Similarly, Boner and Stermitz (1967, p.B1) report that comparable conditions led to the June 1964 floods in northwestern Montana where 30 lives were lost and damages exceeded $55 million (1964 U.S. dollars). These reports, however, are very limited with respect to the potential runoff contributions of other flood causal factors. Aside from a description of the most apparent causal factors, there is rarely any reference to man's influence on the runoff patterns and subsequent flooding.

Rain caused floods have also been documented in Canada by the federal government, Inland Waters Directorate (e.g. Smith 1975; Warner, 1973; and Warner and Thompson, 1974). Warner (1973) examined the June 1964 Oldman and Milk River floods. Extensive flooding was experienced in southwestern Alberta and Montana after heavy rain fell along the foothills, parallel to the eastern slopes of the Rocky Mountains. Warner (1973, p.1) suggests that although the flood was primarily attributed to the heavy rains, other conditions also contributed. Prior to the heavy June rains, precipitation during May 1964 had been 100 percent above normal in the headwaters of the Oldman River basin. The usual snowmelt runoff pattern was late because below normal temperatures were experienced in the region between March and May. As a result, the major melting of the snowpack began in late May and continued into June at a sustained high yield. Warner (1973, p.6) states that these two factors, that is, the unusually

heavy May rainfall and the late snowmelt, created saturated soil conditions and high river levels. Therefore, when the June seventh and eighth storm occurred, the streams responded rapidly and record high yields and flooding were experienced in many areas of the Oldman and Milk River basins. The flood damage was particularly severe in the United States and it is better reported by Boner and Stermitz (1967).

It is interesting to note that the flood in the Oldman and Milk River basins occurred in 1964 and was not reported by the United States Geological Survey until 1967, and by Environment Canada until 1973. These "after-the-fact" reports which are often conducted many years later usually describe only the most obvious flood causal factors.

3.3.2 Snowmelt:

Snowmelt floods have also been well documented (e.g. Anderson and Burmeister, 1970; Brice and Reid, 1975; Environment Canada, 1974; Fraser River Board, 1963; O'Connell and Rostvedt, 1972; Sewell, 1964; and Waananen, Harris and Williams, 1971). As in most of the precipitation flooding reports, snowmelt was generally not the only causal factor referred to. For example, Anderson and Burmeister (1970) reported that the 1965 spring flood in the upper Mississippi River basin was essentially the result of a sudden and heavy snowmelt. However, this snow cover and an impervious frozen ground surface contributed to increased runoff when heavy spring rain storms occurred.

A 1974 Environment Canada publication on the 1973 New Brunswick flood provides a further example of the limited reference to the flood causal factors which potentially contributed to the flood. Environment Canada (1974, p.14) states that the flood was caused by a combination of only two events; heavy snowmelt and storm precipitation. Apparently, by the end of March, snow accumulation in New Brunswick was higher than normal. Some of the snow in the southern region of the province melted during early April, but in the northern areas and upper portion of the Saint John River basin, cool temperatures

persisted and heavy snowfall further increased the water equivalent of the snowpack. In late April most of this snow melted and during this time a major storm dropped over 10 mm of rain in many locations. The already swollen rivers (from snowmelt) flooded with the addition of further runoff. This is a classic report containing most of the same elements and techniques found in other Canadian and American flood reports. There are, however, no references to other causal factors which could have contributed to the flood. The report did not contain reference to the possible yield increases or timing influence on the runoff from areas of the watershed which had been logged (Cheng, 1980; Cheng et al., 1975; Helvey, 1974 and 1980; Hewlett and Helvey, 1970; Swanson, 1978; Swanson and Hillman, 1977a and 1977b). There was no reference to antecedent soil moisture conditions, nor to the possibility of increased runoff from a frozen ground surface. There was also no indication of what effect (if any) urban centers had on the flood peak (Hollis 1975, MacKenzie 1981, McPherson 1974, Taylor 1976, Waananen 1969). Many of the above factors, while often individually insignificant, can have a dramatic effect on peak flows when in combination.

During December 1975, severe flooding was experienced in many river basins in western Washington State. Dunne and Leopold (1978, pp.12-18) report that during November the Cascade Mountains received heavy snowfalls. In early December a large warm, moist atmospheric disturbance moved over Washington and heavy rain fell on the snowpack for five days. Severe flooding resulted, particularly in the Snohomish Valley located northeast of Seattle, and damage has been estimated at roughly $50 million (U.S.). When attempting to attribute the rapid snowmelt runoff and subsequent heavy flooding to other factors, Dunne and Leopold (1978, p.18) claim that "under these extreme conditions, differences of runoff between vegetation and land use types tend to be relatively unimportant." This belief has been expressed by others (e.g. Saskatchewan, Department of the Environment, 1978) who feel that land use changes contribute a greater influence to flood flows during smaller flood events than during major events. This claim will be elaborated on in Chapter IV.

In most of the previous examples concerning snowmelt and rain flooding, only the most apparent flood causal factors have been identified for single flood events in particular locations. Many causal factors which could have contributed to flooding were not identified by the researchers. It is apparent that these micro-flood reports are emphasized too much and that concentrated efforts towards predictive research could prove more useful. This does not mean that these reports are of no value. Much of the information provided in these publications was used to design the classification of the causes of flooding in Chapter IV and to establish flood patterns. It is anticipated that the classification of the causes of flooding will help to tie these isolated flood reports together so that broader general perspectives on flooding in Western Canada can be developed.

3.4 Historical Flood Literature:

When reviewing the literature the author located a third group of flood descriptions which involved a perspective view and historical survey of the flood hazard in a particular region. Many of the references in this group include descriptions of past floods to assist with current management. For example, Rannie (1980), while examining the flood control structures on the Red and Assiniboine Rivers in Manitoba, reviewed many of the previous floods in this area. Rannie (1980, pp.209-213) also examined the flood control system which was designed to reduce the flood risk in the Winnipeg region, with respect to recent flood events. The most recent event (1979) having almost exceeded the record 1950 levels. While these reports contain reference to many of the flood causal factors which are responsible for these events, no classification of these factors is presented.

Numerous flood plain studies, which have been completed by individual provinces and/or in co-operation with the Federal Flood Damage Reduction Program, provide reference to the causal factors affecting a particular location (Alberta Environment, 1980; Beckstead and Garner, 1978; Fisheries and Environment Canada, 1977; Fraser River Joint Advisory Board, 1976; Lowe, 1974; Montreal Engineering Company Ltd., 1968; Outhet and Penner, 1979; Staite, 1979). For instance,

Outhet and Penner (1979 pp.1-2) have completed a flood plain study for Whitecourt, Alberta. They refer to ice jam and rainfall floods which have occurred in previous years, but aside from generalities, there was no reference to the factors which caused these floods. For example, warmer spring temperatures in the southern portion of the McLeod River basin can cause early break-up. When the moving river ice encounters the still frozen Athabasca River to the north an ice jam could form. Flooding from precipitation can be caused by mT air masses which are uplifted by a cold front and/or the foothills.

In Beckstead's (1978) flood plain study of the Oldman River at Lethbridge, there is a short discussion of the causal factors which are usually responsible for flooding in this area. Beckstead (1978, pp.7-8) suggests that rainfall is the main ingredient of flooding, and that snowmelt only contributes to flooding by creating saturated ground conditions and moderate streamflows which allow most streams in a flood area to respond rapidly to storm rainfall. Beckstead (1978, p.7-8) also refers to the meteorological elements which contribute to flooding;

> "the intensity of the rainfall may be magnified by a particular but not uncommon orientation of weather systems. This generally takes the form of low-pressure centers over and just east of the Continental Divide which draw moist air travelling north from the Gulf of Mexico counter-clockwise into an air mass travelling west."

When this moist air reaches the foothills and mountains, orographic lifting can result in intense rainfall. This is one of the most serious precipitation flood types in Alberta and has caused severe flooding in the Peace (Smoky) River basin and other basins. This form of flooding will be discussed further in Chapter IV.

When developing a plan for water management in the Saint John River basin in New Brunswick, the Saint John River Basin Board (1972 and 1975) identified many flood causal factors which had previously caused flooding and could again in the future. The Board (1975, p.99) claimed that "short of a dam bursting, there cannot normally be flooding without excessive rainfall or snowmelt as a primary cause." The board then elaborated on the factors existing in the

basin which could cause flooding. These included ice jams, log and debris jams, failure of small dams, changes in land use (logging resulting in sediment problems), channel constrictions, and urbanization. In their 1972 report, the Board also identified convective storms and hurricanes as major sources of rainfall. The majority of government reports do not usually attempt to identify many flood causal factors, and in this way, the Saint John River Basin Board's reports were somewhat unique.

For reasons stated earlier, the author feels that it is important for the flood factors described in these and the previously cited sources to be brought together. The literature dealing with specific flood events, technical flood characteristics, and flood overviews needs to be consolidated so that patterns which will assist planners to identify the potential flood problems in a specific region may be identified.

3.5 Flood Frequency Analysis:

To date the most common method used to estimate how often certain flood events will occur in the future has been to calculate the frequency, or return periods, of different flood magnitudes using the recorded stream discharge data. Some planners feel that flood frequencies based on the period of record are sufficient data on which to base major flood control and planning decisions. This standard assumption is, however, not necessarily valid. Various combinations of flood causal factors, and the occurrence of "exotic" flood events, may not have occurred during the period of record. Inconsistencies in the recorded data and changes in the causal factors (e.g. land use, drainage, etc.) can lead to incorrect frequency analyses which often result in inaccurate flood damage reduction decisions. This problem is present not only in Western Canada, but also in other areas where similar data inconsistencies and flood frequency determination techniques are employed.

In the following discussion these and other problems related to the existing flood frequency analysis techniques will be discussed. It is anticipated that a review of this type will help illustrate

the need for other techniques to supplement this procedure which in turn will help to improve the flood management decision making process.

3.5.1 Limitations of Flood Frequency Techniques:

Frequency analysis is used by hydrologists to aid in the control of flooding and management of flood plain lands by determining the return period of recorded flood events and predicting the magnitude of larger flood events. Essentially, this involves assigning a return period to a particular river discharge event which can be expressed in terms of either its recurrence interval or its probability. The recurrence interval, which is expressed in years, is the average interval of time within which a given flood level will be equalled or exceeded (Fisheries and Environment Canada, 1977, p.8). For example, hydrologists have calculated that during the 1:100 year flood event on the Bow River there would be a discharge of 2,832 m^3/s above the Elbow River confluence. The probability of the 100 year flood on the Bow River would therefore have a 1% chance of being equalled or exceeded in any given year.

The progression of flood frequency analysis techniques has incorporated more mathematical statistics as the methods of analysis have become better defined. Flood frequency analysis was initially accomplished by plotting data points to an exceedance probability formula such as the Hazen or Weibull position (Stolte and Dumontier, 1977, p.1). A best fit frequency curve was then drawn through the points. These early plots, however, were often done subjectively and the best fit line exhibited curvilinear relationships because the flow extremes were usually highly skewed (Kite, 1977, p.215). A variety of probability papers were designed in an attempt to make the plotted points fit a straight line more closely, but the subjectivity of plotting the frequency curve still existed. These preliminary data plotting and line fitting techniques are described in the literature (e.g. Benson 1962a, Chow 1964, Dunne and Leopold 1978, Haan 1977, Smith and Stopp 1978). Most of the subjective placement of the frequency curve has been reduced by the development of mathematical

techniques. There will be no attempt to discuss the statistical proofs of these techniques since they have been described elsewhere (e.g. Gumbel, 1966; Kite, 1977; Stolte and Dumontier, 1977), and have been studied by Booey at the University of Manitoba and others in the National Research Council Associate Committee on Hydrology.

No general agreement exists among hydrologists as to which of the various theoretical distribution techniques should be used. For example, Spence (1973, pp.130-139) compared the fit of the normal, 2-parameter log-normal, type I extremal and log-type I extremal distributions to annual maximum flows on the Canadian Prairies and concluded that the log-normal was the best fitting technique. Cruff and Rantz (1965) compared six probability distributions in California and concluded that the Pearson-type III was the most accurate. In other studies Reich (1973, pp.291-303) conducted a survey of engineers and hydrologists in the United States and concluded that the log-Pearson type III was preferred over both the extremal type I and the log-extremal type I tests. Santos (1970, pp.63-67) found the log-normal distribution better than the Pearson type III. Stolte and Dumontier (1977, pp.42-43) state that in Alberta the log-normal II distribution and the log-normal III distribution provide fairly reliable estimates of the 100 year flood with short period data. They also state that the log-normal III distribution provides very reliable results for a long term period of record. Stolte and Dumontier (1977, p.42) further conclude that the normal and Gumbel distributions both consistently provide low estimates of the 100 year flood and were, therefore, unreliable. This is a significant finding because the Gumbel distribution is widely used both in the United States and Canada for fitting flows. Alberta Environment (1974, pp.9-10), for example, used the log-Gumbel distribution to estimate the 1:100 year, 1:75 year, and 1:50 year flood discharges for the North Saskatchewan River at Edmonton. The research conducted by Stolte and Dumontier (1977) provided support for the findings of the United States Water Resources Council Work Group (Benson, 1968, pp.891-908).

The Work Group determined that the Gumbel distribution tended

to under-estimate the 100 year flood and that the log-Gumbel distribution over-estimated the 100 year flood. The Hazen method was also rejected by the Work Group on the basis that it is too empirical. The Work Group concluded that the log-Pearson III was the most suitable for application by all agencies. Pentland and Cuthbert (1973, pp.470-473), however, disputed the use of the log-Pearson type III distribution because when applied to the Fraser River basin in British Columbia, the results showed large discontinuities and unnatural flood frequencies. Pentland and Cuthbert claim that the log-normal distribution was more representative in the Fraser River basin. Dunne and Leopold (1978, p.306) add further confusion to the debate when, after looking at the log-normal, Gumbel Type I, Gumbel Type III and Pearson Type III distributions, they state,"the Pearson Type III distribution is slightly more complicated to use...we have not found its results to be any better, or even very different, from those of other methods."

In Western Canada numerous flood studies have been conducted using different methods of frequency analysis. For example, Smith (1975, pp.9-10) used the log-Pearson distribution when analysing the 1971 Fort Nelson flood in northern British Columbia because it was recommended by the Hydrological Committee of the Water Resources Council of the United States Government. Most published flood reports in Western Canada, however, do not state the nature of the frequency analysis conducted, but only release the computed results. For instance, Warner and Thompson (1974, pp.19-20), while reporting on the 1964 Oldman River flood in southern Alberta, published all the frequency data but did not reveal what statistical procedures were used to determine their values. Warner and Thompson, however, did appreciate that short-term periods of record cannot satisfactorily define short-term floods. Many other authors, both federal and provincial, appear to observe this practice (Alberta Environment, 1978, 1979, 1980; Fisheries and Environment Canada, 1977; Fraser River Joint Advisory Board,1976; Thompson,1973).

It is apparent from this discussion that no single flood frequency distribution technique has been accepted as accurate or universally applicable. In British Columbia, for example,

the Ministry of Environment is currently using four frequency distribution procedures to estimate discharges for various return periods; the log-normal, Gumbel, Pearson type II and the log-Pearson type III. Using a modified version of the Kolmogorov-Smirnov test (goodness-of-fit) and other criteria, the distribution which appears to best represent the streamflow data is selected. However, the decision concerning which distribution to use is not always straight-forward and despite the expertise of the hydrologists, subjectivity can still be a problem. Like most other hydrologists, they are working with what is presently available while concurrently attempting to improve the existing techniques. This problem also exists in many other areas of the world. Stolte and Dumontier (1977, p.43) state that "the fact that no totally reliable method is available for estimating the 100 year flood, regardless of the period, cannot be over-stressed."

3.5.2 Limitations in the Period of Record:

Most hydrologists and hydraulic engineers presently involved in the computation of flood flows use the period of streamflow record as the input data for frequency analysis, even in areas of very short-term records. Essentially the nature of the data which can be abstracted from the period of record is either of an annual or partial duration type (Kite, 1977, p.215). The annual series data consists of the single largest recorded flow for each year on record (one discharge figure per year). The partial duration series includes all events above a predetermined river discharge level. While the partial duration series provides more data for analysis, it is difficult to select an arbitrary base flow and subjectivity can occur when regarding the independence of an adjacent event. For example, closely consecutive flood peaks may actually be in one flood. In most flood frequency analyses, therefore, the annual series data are used most often because they are easiest to abstract and analyse. One problem with the annual series data is that the second largest flood event in a given year may outrank many other annual floods on the period of record. The annual series data are plotted and a statistical

technique is used to find the best fit frequency curve through the data points (described in the previous section).

The period of record is often not long enough to contain all the possible combinations of flood causal events which can occur. If a long period of record existed (100,000 years) without climatic and other changes then it would be relatively simple to establish the frequency patterns directly from the recorded data. In Canada and the United States, however, the period of record is often too short and in many cases is well under 30 years. Dalrymple (1960, p.14) and Kite (1977, pp.13-16) are among many hydrologist who feel that properly authenticated historical events can be used to extend the relatively short period of record and increase the accuracy of the analysis. This is partially correct, but in Western Canada the use of historical data would not sufficiently lengthen the period of record for analysis. Klemes (1980, p.10) states that historic streamflow records are "ridiculously short" for any attempt to study the frequencies of flooding.

Another problem associated with using a limited period of record is that the various types of flood events may not be representative of the potential range of flood events which could occur over a longer period of time. Different flood causal factors have different recurrence frequencies and the presence or absence of a less frequent event can cause substantial inaccuracies and distortions in the frequency analysis. For example, the occurrence of Hurricane Hazel (1954) in a relatively small area of Ontario (concentrated over approximately 100 square kilometres in the basins of Credit and Humber Rivers and Etobicoke Creek) was a very rare event and the flood discharge which resulted from the rainfall was far greater than any previous event on record. The federal and provincial governments have taken the rain intensities and runoff responses from these small river basins and applied the same precipitation patterns to the Grand River basin (and others) to estimate the 1000 year flood event. The Grand River basin, which is very large, could absorb much of the impact of the same type of storm rainfall far better than a small river basin. The result of this transfer from small to large

river basins has resulted in the upward skewing of the frequency curves for many southern Ontario rivers, giving a false impression for many flood return periods (Klemes, 1980, p.11). As a result, the frequency curves for many of the rivers in the affected area of Ontario were skewed upwards giving a false impression of the 100 year flood (Klemes, 1980, p.11). Similarly, the 1964 Alaska earthquake generated a wave train of tsunamis which severely damaged Port Alberni and other centers on the west coast of Vancouver Island. Yet this event was the only documented case of tsunami damage on the west coast of British Columbia which has been scientifically recorded. Is it possible to determine a frequency pattern for single events of this type? The previous examples are only two of many isolated events which have occurred in Canada, and the period of record is not capable of providing sufficient data to determine the return period of these "exotic" events.

Extreme flood events can occur as a result of a combination of different flood causal factors. Once again, these extreme events are frequently not present in the period of record more than once, if at all. For example, a series of unusual meteorological events resulted in a very severe flood in the Big Thompson Canyon, Colorado in 1976;

> "Moisture from both the Gulf of Mexico and the Arizona monsoon had fed into the Colorado high country for 48-72 hours prior to and during the flood. This moisture influx provided the 'fuel' for the flood and insured that a conditionally unstable and moist environment would exist over the flood area. A chilled mass of polar air spilled off the Canadian prairies across the northern and central plains on Friday and Saturday, 30-31 July. As the leading edge of this cooler air slipped slowly across eastern Colorado on Saturday, it converged very moist air toward the Colorado foothills. The slow movement of the cold air boundary helped to direct the strongest moisture convergence toward the thunderstorm system producing the flood rains." (Henz and Schutz, 1976, p.280)

Other details of the Big Thompson flood are provided by Henz and Schutz (1976, pp.278-285), but it is important to note that this unusual flood was intensified by the rain falling on soils with a low storage capacity and which were situated on steep slopes. The precipitation measured over 188 mm in a four hour period and the flood caused 139 deaths.

If, during the period of record, no major flood events have occurred the opposite effect can result. The potential may exist for the occurrence of an "exotic" event, but if such an event has not happened during the period of record then the frequency curve can be skewed downwards. The City of Calgary provides one of the most controversial and potentially serious flood situations in Western Canada. The townsite, which is situated in the Bow River basin, has experienced no extreme floods during the period of record, but there have been several significant flood events. The following case study of the Calgary situation is included because it is one of the major flood concerns in Western Canada and is representative of a center with a flood potential which is often ignored.

Prior to the start of instrumented streamflow measurements on the Bow River in 1908 the City of Calgary experienced numerous floods in the late 1800's. The largest of these occurred in 1897 with an estimated maximum instantaneous discharge of 2265 m^3/s (Fisheries and Environment Canada, 1977, p.36). In 1902, another serious flood occurred which had an estimated maximum instantaneous discharge of 1557 m^3/s (Fisheries and Environment Canada, 1977, p.36). Since streamflow measurements began in 1908, the City of Calgary has not experienced a major flood event. Two large floods (1929 - 1343 m^3/s; 1932 - 1500 m^3/s) have occurred since 1908, but neither closely approached the estimated 1:100 year flood discharge of 2,832 m^3/s (above the Elbow River junction) calculated by the Montreal Engineering Company (1968, p.5). The comparitively small annual river discharge events which have been measured on the Bow River since 1908 have skewed the calculated frequency curve downward, which provides a distorted impression of the potential flood hazard. Despite this false impression, however, the potential for a major flood to occur on the Bow River at Calgary is still very high. Thompson (1976, pp.1-11) has reported on two major rainfall floods (1872 and 1902) which occurred in the Bow River basin upstream from Calgary prior to the beginning of the period of record in 1908. The Water Survey of Canada has determined that there is approximately a 30% probability in any given year that a severe rainfall event will

occur somewhere along the eastern slopes of the Rockies from Montana to central Alberta (Alberta Environment, 1980, p.4). It is only by chance that such events have not occurred in the Bow River basin in the past 73 years.

Usually the major cause of flooding in the Bow River basin results from rainfall on the eastern slopes of the Rocky Mountains in combination with saturated ground conditions, snowmelt and many of the lesser contributors such as urban runoff, land drainage and changes in the watershed surface. In past years, these conditions have combined to cause significant flooding in the river basins to the north and south of the Bow River basin. In the North Saskatchewan River basin at Edmonton, major spring discharges have occurred in 1915, 1944, 1952, 1954, 1965, and 1972 (Water Survey of Canada, 1977, p.220). The Red Deer River at Drumheller has flooded seven times since recording began in 1915; 1915, 1920, 1923, 1948, 1951, 1952, and 1954 (Staite, 1979, pp.67-78). To the south of Calgary, the Oldman River at Lethbridge has experienced significant flood discharges in 1923, 1942, 1953, 1964, and 1975 (Water Survey of Canada, 1977, p.232). Therefore, the potential for flooding in Calgary appears to be high. Numerous floods have occurred in the river basins to the north and south of the Bow River basin since 1908, and it appears as though it may be just a matter of time until Calgary experiences a major flood. In June of 1981 heavy rainfall in the Bow River basin produced saturated ground conditions. By June 9, the upstream reservoirs were full and releasing at maximum discharge. Cole (personal interview, June 10, 1981) suggested that if a heavy rainfall occurred during that time, Calgary would experience severe flooding. Rain followed on June 11 and 12, but no serious flooding occurred although the Bow was extremely high.

The absence of any severe floods in recent years and the unjustified expectation that reservoirs upstream will limit future flooding has led many people (including some in city council) to believe that serious floods will not occur again in Calgary. The preceding evidence and earlier records for the Bow River, however, show this attitude to be nothing more than wishful thinking. A significant

portion of Calgary has been constructed on the flat Bow and Elbow River flood plains. Districts in Calgary which are particularly susceptible to the 100 year flood(2,832 m^3/s) include Bowness, Parkdale, Hillhurst, Sunnyside, Downtown, Bridgeland, and Inglewood. The municipal and provincial governments have allowed developers to construct residential, business and industrial structures along the flood plain despite the many reports which have clearly defined the flood zones, and proposed a number of solutions (Montreal Engineering Co. Ltd., 1968 and 1973; Alberta Environment, 1980). Public and business pressures, however, have blocked the implementation of many of the proposed flood damage limitation measures. Few of the current flood plain inhabitants, however, were present during the last flood event in 1932 (1500 m^3/s) which was far below the estimated 100 year flood of 2,832 m^3/s. These people tend to believe that the power dams upstream on the Bow River will control any future floods (Osborn, 1975, p.49). Burton, Kates and White (1978, pp.35-36) suggest that a common problem with flood plain development is that the inhabitants tend to live with a false sense of security when structural controls exist upstream. Laycock (personal communication, March 1980) suggests that it is not likely that any of the dams upstream of Calgary could be effectively used for flood control as they were designed for storage and head for electric power needs, and would usually be full during the flood period. During the spring, the reservoirs usually fill up before the flood threats involving mT air masses might occur (refer to causal factor, II.a). If provision for flooding were included some releases might be realized, but these would be limited. The reservoirs need to be filled as high as possible during the spring so that sufficient water is available for power production through the low flow periods of late summer and winter. Therefore, it is not possible to allow a major lowering of the reservoir levels on the assumption that a flood "might" occur. If the reservoir levels are not maintained, power production would be seriously limited. There are, therefore, no grounds for the common belief that the existing upstream dams in the Bow River basin would control flooding in Calgary.

Klemes (1980, p.9) adequately summarized this section when he stated;

> "The present flood frequency analysis practiced by hydrologists is largely irrelevant to the problem the name of which it carries. The help that hydrologists were hoping to get from classical statistics is grossly inadequate because it arbitrarily relies on tools developed for different purposes and because it is rooted in inadequate hydrological understanding of the phenomenon of interest. It is not to the hydrologists' credit that they have devoted so much time and effort to the endless variations of frequency distribution fitting without paying much attention to the nature of floods itself. The knowledge that is necessary here cannot come from hydrology alone. It must also come from climatology and meteorology since a flood is the end-result of climatic, meteorologic and hydrologic processes."

With more intense use of flood plains and other flood-prone areas, we must develop a better understanding of flood causes for better analysis. It is, therefore, imperative that flood planners take a broader, more comprehensive approach to flood management. Use of other supplementary tools such as a flood causal classification would help us to use flood frequency analysis. The planner would have a better basis for flood forecasting and decision making.

CHAPTER FOUR: A CLASSIFICATION OF CAUSES OF FLOODING

4.1 Introduction:

In earlier chapters it has been clearly stated that the purpose of this research is to develop a classification of a wide range of the factors which can cause and/or contribute to flooding in Western Canada. An information base of this type would supplement existing flood forecasting methods and contribute to a better understanding of the various flood causal factors, thereby providing a solid foundation for planning and decision making. In this chapter, a classification of many of the potential flood causal factors found in Western Canada is presented. A more detailed description of each of the major flood causal factors follows the classification with reference to potential distribution patterns and management alternatives.

4.2 The Classification:

Piper and Ward (1929, p.279) define classification as, "any orderly grouping of objects which exhibits their mutual relationships. It is usually concerned with likeness and differences, and the proper subordination of classes." There are two main types of classification; general or "natural" classifications, and specific or "artificial" classifications. Piper and Ward (1929, p.280) suggest that an artificial classification is based on some superficial or accidental characteristic which is arbitrarily chosen or assigned to a class of objects. For example, the classification of the letters in the Roman alphabet according to their shape. A natural classification, however, is a scientific approach based on the ordering or sorting of objects according to some essential property. Harvey (1973, p.332) claims that a natural classification should be based on resemblance, that is, the objects must show certain affinities.

One of the objectives of this research is to order the causes of flooding and the factors that contribute to variations in flood intensity for better use and understanding by water planners. It was determined, therefore, that this "ordering" should be based

on the distinct relationships of the flood causal variables. As defined above, this ordering, or classification, would be "natural" because the flood causal factors can be sub-divided into specific categories and classes.

Chow (1964, p.14-4) suggests that from a hydrologic point of view, the runoff regime patterns from a drainage basin may be considered, in part, as a product of the physiographic factors present. In addition to those physiographic elements discussed in Chapter II, these factors would include the characteristics of the drainage basin such as the size, shape and slope of the drainage area, the permeability and capacity of the ground water formation, and the presence of lakes and swamps. While in agreement with Chow, it is this author's contention that most of these physiographic factors are very slow in changing. Therefore, the classification of the causes of flooding will be based on the factors which can occur despite the "fixed" physiographic factors. Many of the physiographic factors suggested by Chow are important in causing variations from basin to basin and reference will be made to them where it is considered necessary.

Many of the flood causal factors (herein referred to as causal factors) are not independent events and often interact with other causal factors in the classification. For example, dam failures (causal factor VII.c.2) are often caused by design errors, but could also occur from excessive runoff resulting from an intense rainstorm (causal factor II.a). Similarly, the ice jams at Fort McMurray can be caused by a variety of factors, including early break-up in the headwaters of the Athabasca River (causal factor I.a.1), grounded slab ice (causal factor I.a.2), river gradient changes at Fort McMurray (causal factor I.a.4), or a combination of these factors. Potential interaction between the flood causal factors had to be considered while designing the classification. It was, therefore, not possible to simply divide the causal factors into natural and man-influenced categories.

Initially a list of twenty-seven flood causal factors present in Western Canada was compiled. This was done through an intensive

literature review, and personal communication with government officials and university professors, especially Dr. A.H. Laycock of the Department of Geography at the University of Alberta. This compendium of causal factors was then divided into nine major categories based on common characteristics. After further research, the author found that many of the causal factors in the nine categories had more than one origin. Therefore, the causal factors were again divided into subcategories based on innate differences between them. Table 4.1, which has been included for easier reference, illustrates the hierarchy of the classification. For example, Natural Channel Blockage (the first major category) is subdivided into six subcategories; a) Ice Jams, b) Glacier Activites, c) Landslides, d)Vegetation Constriction of the River Channel, e) Sediment Deposition, and f) Debris Jams. Each of these subcategories have common grounds in that all six can contribute to flooding by blocking a river channel. There are, however, differences within each of these subcategories. Ice Jams, for example, can be further divided into six other sections, and Sediment Deposition into three sections. The classification of the causes of flooding in Western Canada is presented in Table 4.2.

While direct reference to the categories of "natural" and "man's influence" have been omitted, it is possible to unofficially separate the classification into sections for general reference purposes. Sections I to VI inclusive could be considered as natural flood causal factors, and sections VII to IX as causal factors associated with man's activities. It would be wrong, however, to make such clear distinctions because in many cases man's activities often cause and/or influence the natural causal factors. For example, sediment deposition in rivers (causal factor I.e.1) can occur naturally, but the origin of the sediment may be related to man's activities. This is the case in the Swan River basin in Alberta where oil exploration and development activities have caused extensive soil erosion. Much of the eroded material has been deposited at the mouth of the Swan River and along the river channel, and has been the main cause of flooding in recent years (further discussion of this situation is presented in section 4.3.1.5.a). It is interesting to note that

TABLE 4.1

FLOW DIAGRAM: CLASSIFICATION OF THE CAUSES OF FLOODING IN WESTERN CANADA

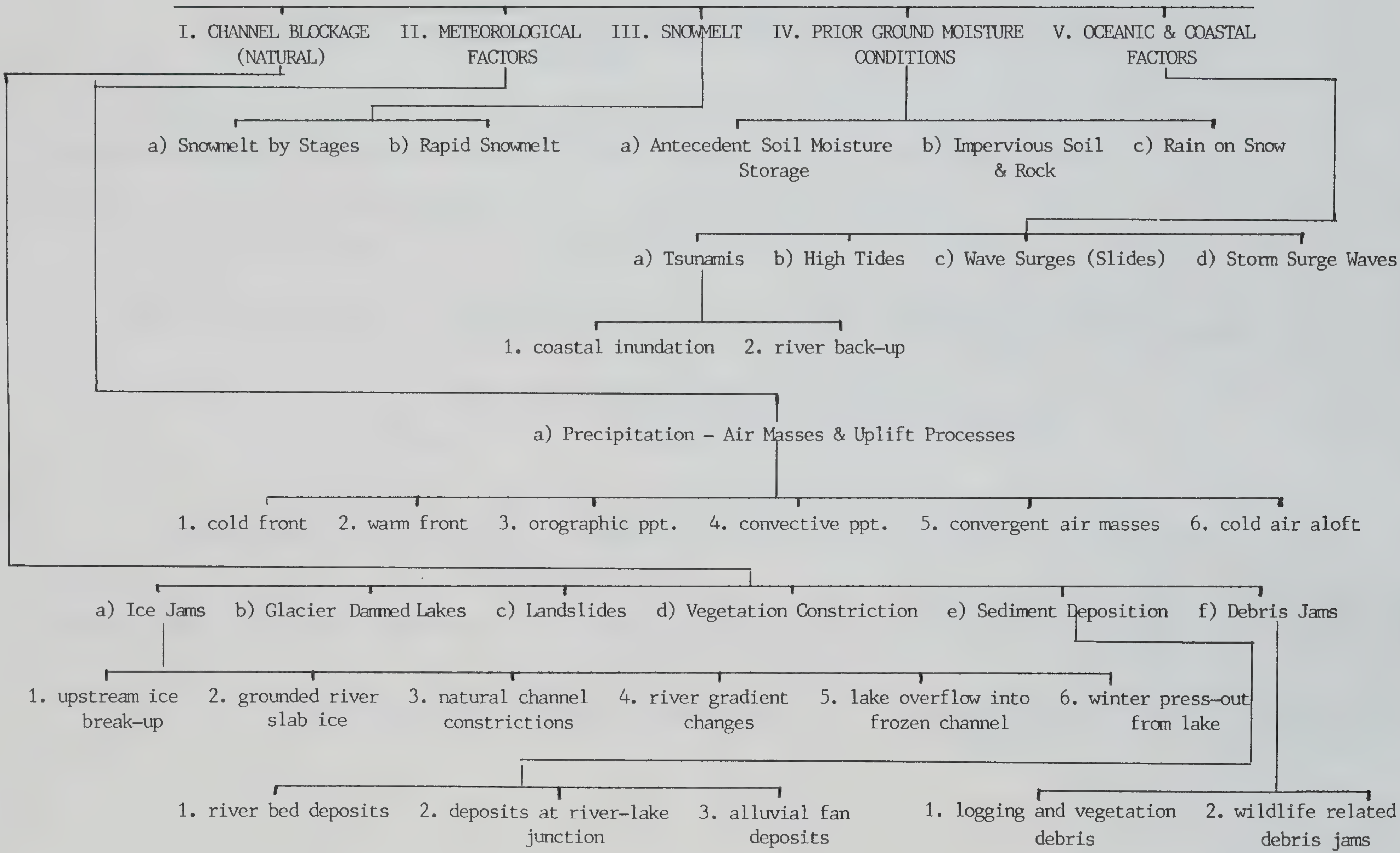


TABLE 4.1

FLOW DIAGRAM: CLASSIFICATION OF THE CAUSES OF FLOODING IN WESTERN CANADA (CONT'D)

- VI. LAKE FLOODING
  - a) Landslide Wave Surges
  - b) Precipitation Runoff
  - c) Winter Press-Out (Lake)
  - d) Post-Glacial Flooding
- VII. ENGINEERED RIVER CHANNEL OBSTRUCTIONS
  - a) Bridges
    - 1. ice jam formation
    - 2. debris jams
    - 3. peak flow diversion
  - b) Land Fill and Dykes
    - 1. reduced channel capacity
    - 2. channel constriction; ice jams
    - 3. dyke flow constriction
  - c) Dams
    - 1. ice jams
    - 2. dam failure
    - 3. dam over-topping
- VIII. LAND USE CHANGES
  - a) Forest & Wild Fires
    - 1. increased runoff
    - 2. erosion & sedimentation
  - b) Logging
    - 1. increased runoff
    - 2. erosion & sedimentation
  - c) Road Construction
    - 1. changes in natural runoff
    - 2. erosion & sedimentation
  - d) Land Drainage
  - e) Urbanization
    - 1. impervious surfaces & storm sewers
    - 2. urban development on the flood plain
- IX. INTERBASIN TRANSFERS

where man has engineered a flood protection obstacle, he has often created or added to the potential for flooding elsewhere (causal factors VII, b&c).

It is important to understand and appreciate that the following classification of the causes of flooding is an initial attempt to identify those factors which cause and contribute to flooding in Western Canada. It is not expected to be the final word on the subject, but is primarily designed to provide a basis and stimulus for further research and analyses.

TABLE 4.2: CLASSIFICATION OF THE CAUSES OF FLOODING IN WESTERN CANADA

I. Channel Blockage (Natural):

a) Ice Jams:

1. Upstream ice break-up:

Occurs when warm temperatures in the southern portion of a river basin cause the river ice to break-up, flow northward, and jam against the still solid river ice in the colder northern regions of the basin. Occurs also where tributary ice breaks-up before the main river or lake ice, and jams form at the confluence of the two rivers or at the river mouth. Examples: Dawson (Y.T.); Whitecourt (Alta.); Fort Simpson and the Town of Hay River (N.W.T.) (refer to Section 4.3.1.1).*

2. Grounded river slab ice:

Occurs when masses of slab ice ground on the river bed. Examples: Hay River (N.W.T.); Fort McMurray (Alta.); at various points along the Mackenzie River (refer to Section 4.3.1.1).

3. Natural channel constrictions:

The most common sites for this type of jam are where river channels are narrow and/or bend sharply. Can also be caused by periodic freezing along the river bank as was the case in Calgary prior to the Bearspaw Dam. Examples: Dawson (Y.T.); Thelon and Kazan River basins; and the Ramparts on the Mackenzie River (refer to section 4.3.1.1).

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* Reference following each flood causal factor indicates where further detail and comments can be located in Section 4.3 of this chapter.

4. River gradient changes:

Can occur where the gradient of a river decreases substantially (water velocity decreases). Example: Fort McMurray (Alta.).

5. Lake overflow into a frozen channel:

Can occur where the head in a still ice free lake is sufficient to discharge into a frozen river channel, break the ice, and form an ice jam against the more solid downstream ice. Example: Baker Creek (near Yellowknife, N.W.T.) (refer to Section 4.3.1.1).

6. Winter press-out from a lake:

Occurs when snow falls on an ice covered lake and near freezing water is squeezed out and down the already frozen discharge stream. Water freezes in the stream channel and out over the river banks (not a "true" ice jam). Examples: Baker Creek basin (near Yellowknife, N.W.T.); Copper River and many other areas in the N.W.T. (refer to Section 4.3.1.1).

b) Glacier Activities:

1. Glacier dammed lakes and outburst floods:

Can occur where a glacier surge dams a river channel or blocks an ice free valley. A lake can also form when two glaciers converge. Severe flooding often occurs when these lakes are released. Examples: Summit Lake (B.C.); Tulsequah Lake (B.C.); Tweedsmuir Glacier (Alsek River, B.C.); Steele Lake (Y.T.) (refer to Section 4.3.1.2).

c) Landslides:

1. River blockage:

When a slide blocks a river channel, water backs

up and localized flooding can occur. Would occur most frequently in the steep walled valleys of the Cordillera. Examples: Frank Slide (near Frank, Alta.); Snoqualmie Pass (Washington State, U.S.A.), Jan. 25, 1982 (refer to Section 4.3.1.3).

d) Vegetation Constriction of River Channel:

Where vegetation is in the river channel and/or along side the channel it can cause a discharge lag and back-up which often results in flooding and diverting of flow onto the flood plain. Examples: Sturgeon-Weir River (Sask.); Muskeg areas in Northern Canada (refer to Section 4.3.1.4).

e) Sediment Deposition:

1. River bed deposits:

When large volumes of sediment are deposited in a river channel the capactiy of that channel is reduced. During high yield the channel cannot hold the same volume of water and flooding can result. Examples: Bow, Swan, Elbow, Oldman, and Paddle Rivers (Alta.); Lower Fraser River (B.C.) (refer to Section 4.3.1.5).

2. Deposition at river-lake junctions:

When sediment is deposited at the mouth of a river (where it enters a lake) a sediment build-up can cause the river to flood during high discharge periods. Example: The mouth of the Swan River at Lesser Slave Lake (refer to Section 4.3.1.5).

3. Alluvial fan deposits:

Severe flooding can occur on alluvial fans during snowmelt and intense rain storms. This can be a major problem if urban developments are located on the fan. Examples: Golden (B.C.); Waterton (Alta.). (refer to

Section 4.3.1.5)

f) Debris Jams:

1. Logging and other vegetation debris:

When debris jams and blocks a river channel, water can back-up behind the "dam" causing flooding both upstream and downstream (in the event of a sudden release). Examples: Coquihalla River, southwest British Columbia, Dec. 27-30, 1980; Saint John River (N.B.).

2. Wildlife related debris jams:

Flooding can occur when wildlife (beavers) construct dams on small creeks and streams. The water back-up can impede flow or a sudden release can occur during intense rainfall and/or runoff conditions. Examples: Drainage waterways in the Leduc region (Alta.), April 1981; Other regions in Western Canada which beavers inhabit close to man's developments.

II. Meteorological Factors:

a) Precipitation - Air Masses and Uplift Processes:

Although a number of air masses influence the meteorological conditions in Western Canada, the maritime polar (mP) and maritime tropical (mT) air masses provide most of the moisture for precipitation. The mP air mass originates over the North Pacific Ocean and can drop large amounts of winter rain on the coast of B.C. and snow on the Cordillera. The mP air masses tend to dominate in Western Canada. The mT air masses are warm, moist air masses which originate over the Gulf of Mexico and Atlantic Ocean. These air masses (mT) can provide large amounts of spring and summer precipitation on the southern prairies and, on occasion, in the north-central areas of Western Canada. The following uplifting processes and meteorological

factors can combine in various ways. (refer to Section 4.3.2.1).

1. Cold fronts:

Cold fronts act like a wedge, forcing warm air upwards. They can cause heavy precipitation on the leading edge depending on the characteristics of the warm air. Examples: June 1964 flood in Montana and S.W. Alberta; June 1972 Smoky River basin flood (refer to Section 4.3.2.1).

2. Warm front:

Occurs when a warm air mass, often associated with a Pacific cyclonic front, rides over cold surface air. There is usually a gentle slope on the front rise. The warm air overrides the cold air and the precipitation amount is dependent upon the characterisitics of the warm air, but it is usually not as intense as precipitation from a cold front. Examples: 1981 and 1982 southern B.C. winter floods; onset of storm sequences involving mT air masses in the Prairies (refer to Section 4.3.2.1).

3. Orographic precipitation:

Occurs when an upland formation obstructs and forces a moist air mass upward and causes cooling and condensation. Heavy rainfall is often caused by this uplift mechanism. Orography may be the sole cause of uplift or it may add to other uplift (e.g. cold front), and the combined effect may result in very intense precipitation. Examples: June 1964 Milk River basin; 1980 and 1981 December rain floods on the coast of British Columbia; Colorado, June, 1965 (refer to Section 4.3.2.1).

4 Convectional precipitation:

Occurs with a vertical rise of warm, moist air. Much of the Plains summer rainfall is from this type

of uplift. Other uplift mechanisms often work in combination with convectional uplift. For example, convectional uplift can result from convergence or from unstable air masses in a warm sector and also from the heat of condensation additions with precipitation on cold fronts. Examples: Regina, June 26, 1975; Winnipeg, May 20, 1974; Smoky River Basin, June 1972 (refer to Section 4.3.2.1)

5. Convergent air masses:

When two air masses with different physical characteristics meet, extensive atmospheric disturbances can result when the warmer, less dense air mass rises over top of the colder, denser air mass. Examples: June 1972 Smoky River basin (Alta.); eastern slopes of the Rocky Mountains (Alta.) (refer to Section 4.3.2.1)

6. Cold air aloft:

This factor contributes to unstable conditions. It is fairly common in Western Canada if air masses moving from Siberia are modified in their lower levels by passage over a limited area of ocean (N. Pacific, Bering Sea, etc.), and arrive still cold at higher levels. The surface warming of the lower moist air results in accentuated amounts of convectional uplift because of the cold air aloft. There is also an increase in precipitation (refer to Section 4.3.2.1).

III. Snowmelt:

a) Normal Snowmelt By Stages - A Contributing Factor:

The gradual rise of the freezing level generally results in a moderately slow runoff. While this factor does not usually cause flooding it can contribute if in combination with another factor such as rainfall. This factor can provide high discharges. Examples: Colorado, 1965; British Columbia, most years; South

Platte River, Colorado, 1965 (refer to Section 4.3.3 for details).

b) Rapid Snowmelt - Spring and Winter:

Can occur when a very warm period suddenly occurs after a cold spell. In the Cordillera, a sudden rising of the freezing level will cause rapid snowmelt. Examples: Fraser River basin, Spring, 1948; Southwestern B.C., December 1979 and 1980. Will also occur when late heavy snowfall is followed by warm temperatures. Examples: Southern Saskatchewan and Manitoba, April 1979; Cypress Hills (Alta.), 1952 (refer to Section 4.3.3.2).

IV. Prior Ground Moisture Conditions:

a) Antecedent Soil Moisture Storage:

Where there are saturated soil conditions from snowmelt and/or long-term rainfall, rapid, unhindered runoff can result because the ground is unable to absorb the waters. Examples: Carrot River (Sask.), 1957; Oldman and Milk River basins (Alta.), 1964; South Arkansas, May 1968; East-Central Alaska, 1967; Cypress Hills (Alta.), 1952 (refer to Section 4.3.4.1).

b) Impervious Soil and Rock:

Where the ground surface is impervious, such as rock, precipitation runoff occurs rapidly because there is little absorption by the ground surface. In areas such as the Shield and Cordillera, there is little lag time following a major rain storm and runoff can rapidly contribute to peak flows. Impervious soil conditions can also be created when an ice cover forms over the ground surface or when "concrete" ice forms in soils as a result of rains and saturation before fall freezing. Example: Cypress Hills (Alta.) 1952. Can also include low infiltration capacity clays when precipitation intensity exceeds the infiltration capacity. Example: Swan Hills (Alta.) with exposure of these soils in drilling areas,

roads, etc. (refer to Section 4.3.4.1)

c) Rain On Snow:

When rain falls on snow a very rapid runoff can occur which can significantly contribute to flooding. This occurs frequently during the winter along the southern coast of British Columbia. There is a potential for this causal factor in most other areas of Western Canada in spring. Examples: December 1979, 1980 and 1981, southwest British Columbia; Winnipeg (Man.), 1950 (refer to Section 4.3.3.2).

V. Oceanic and Coastal Factors:

a) Tsunamis:

1. Coastal inundation:

Tsunamis associated with earthquakes can cause localized flooding along low coastal areas of British Columbia. Example: Port Alberni on Vancouver Island following the 1964 Alaska Earthquake (refer to Section 4.3.5.1).

2. River back-up:

If a tsunami surged up a river channel it could potentially cause the river to back-up, flooding portions of the flood plain. If the tsunami waves were large enough and the river at a high stage, the potential for flooding could be increased. This could occur on any number of rivers along the coast of British Columbia, i.e., Somass River at Port Alberni (refer to Section 4.3.5.1).

b) High Tides:

At certain coastal locations in Western Canada high tides in combination with wave action and wind can result

in localized flooding. Examples: Tuktoyuktuk, N.W.T.; Denmark and West Germany, Nov. 1981; Portions of the North American coastline opposite the Beaufort Sea (refer to Section 4.3.5.2).

c) Wave Surges From Slide Activity:

Where an ice mass or landslide drops into the water and causes a displacement wave. The effect is usually increased in a fiord which funnels the water surge. There is a very low return frequency for any single location. Example: Lituya Bay, Alaska "Pan Handle", 1958 (refer to Section 4.3.5.3).

d) Storm Surge Waves:

Where the major storms cause wind-pushed wave surges in combination with other factors, flooding can result in low coastal areas. Example: Coastline in Yukon and Northwest Territories on the Beaufort Sea in 1970 (refer to Section 4.3.5.4).

VI. Lake Flooding:

a) Landslide Induced Wave Surges:

See flood causal factors V.c and VII.c.3 (refer to Section 3.4.6.1).

b) Lake Level Fluctuations:

1. From precipitation runoff:

Where heavy runoff from snowmelt and/or rainfall increases the level of a lake, shore line flooding can result. Examples: Lake Winnipeg, Lake Manitoba (Man.); Waterton Lake, Lesser Slave Lake (Alta.) (refer to Section 4.3.6.2).

c) Winter Press-Out From Lakes:

See flood causal factor I.a.6 (refer to Section 4.3.1.1).

d) **Post Glacial Flooding:**

Where a river flows out of an upland area and onto a lacustrine plain a fan forms. The river forms its own flood plain on the flat post-glacial lake bed. The streams are not capable of carrying a heavy sediment load on the flat lacustrine plain and deposition occurs and a flood plain forms (early stages of Formation). During high flow periods the channel often cannot contain the runoff and flooding results. Examples: Paddle River (Alta.); Red River (Man.); Carrot and Assiniboine Rivers (Sask. and Man.); Dauphin River (Man.).

VII. Engineered River Channel Obstructions:

a) Bridges:

1. Ice jam formation:

Where bridge piers are located in the river channel and obstruct river ice flows. Ice jams up against the piers and dams the channel, causing local flooding. Examples: MacEwan Bridge, Ft. McMurray; McQueston Bridge, Dawson (Y.T.); Langevin and Center St. Bridges, Calgary (Alta.) (refer to Section 4.3.1.1).

2. Debris jams:

Where bridge piers are constructed in the river channel and the bridge is built low to the river. During high stage periods debris is jammed against the bridge and water can pool, often flowing over the river bank. Examples: Bailey Bridge, Ft. Nelson, 1971 flood (B.C.); Hillhurst and Center St. Bridges in Calgary, during the 1902 and 1932 floods (refer to Section 4.3.7.1).

3. Diversion of water at peak flow:

Where low bridges are constructed over the river channel flooding can occur during high river stages.

The bridge could obstruct flow and divert it onto the flood plain. Example: Hillhurst Bridge, Calgary (1902, 1932) (refer to Section 4.3.7.1).

b) Landfill and Dykes:

1. Landfill – reduced channel capacity:

See causal factor I.e.1. Man reduces the capacity of the channel and often during high yield periods the river cannot accommodate the discharge levels it could prior to the landfill, and flooding results. Examples: Bow River, Calgary; Red Deer River at Drumheller (refer to Section 4.3.7.2).

2. Landfill – channel constriction; ice jam formation:

See causal factor I.a.3. Example: St. Georges Island, Bow River, Calgary, 1975 (refer to Section 4.3.7.2).

3. Dyke constriction of flow:

Where dykes constrict flow on a river there is reduced channel storage and as the high stage flow leaves the confines of the dykes it can spill-out over the flood plain. At this point the river channel capacity is exceeded, that is, downstream from the dykes there is less channel capacity than in the dyked section of the river. Examples: Mississippi River; The Red River in Winnipeg (Man.) (refer to Section 4.3.7.2).

c) Dams:

1. Winter release; ice jam floods:

During the winter, releases from dams for power generation can break-up the ice cover downstream causing ice jams to form where the broken ice is forced against

solid ice (the same effect as flood causal factor I.a.1). Channel constriction from ice during low flow periods, especially where there is peak power fluctuations. Examples: Mayo River Dam (Y.T.); The Town of Peace River, Alberta (Bennet Dam, B.C.) (refer to Section 4.3.1.1).

2. Dam failure:

Severe flooding can result when a dam fails from; spring runoff flowing over the top of a dam; earthquake initiated collapse; and dam undermining. Examples: Duncairn Dam, 1952; Val Marie Dam, 1952; Fourth Lake Dam, 1961; Scott Falls Dam, 1923 (refer to Section 4.3.7.3).

3. Dam over-topping:

Where the design flood is exceeded or where landslide produced wave surge over-tops a dam, flooding could result. Many of the dams in British Columbia have a potential for this type of flooding. Examples: Vaiont Dam, Italy, 1963; Mica Dam (B.C.) (potential) (refer to Section 4.3.7.3).

VIII. Land Use Changes in the Watershed:

a) Forest and Wild Fires:

1. Increased runoff:

When a fire removes the vegetative cover from a portion of the watershed, precipitation runoff can increase significantly as there is reduced moisture detention and interception and infiltration capacities may be reduced. Snowmelt can occur more quickly because there is no shade cover. Various studies in British Columbia and elsewhere have shown that this early, increased runoff can contribute to peak flows (refer to Section 4.3.8.1).

2. Erosion and sediment deposition:

Refer to flood causal factors I.e.1 and I.e.2 (refer to Section 4.3.1.5).

b) Logging:

1. Increased runoff:

Refer to flood causal factor VII.a.1 (refer to Section 4.3.8.2).

2. Erosion and sediment deposition:

Refer to flood causal factors I.e.1 and I.e.2 (refer to Section 4.3.1.5).

c) Road Construction:

1. Changes in natural runoff patterns:

Refer to flood causal factor VII.a (refer to Section 4.3.1.5).

2. Erosion and sediment deposition:

Refer to flood causal factors I.e.1 and I.e.2 (refer to Section 4.3.1.5).

d) Land Drainage:

Removal of surface water detention adds increased runoff to the channel, increases the peak flows during high yield periods, and is especially apparent during low to mid-range flood events. Examples: Moose Jaw (Sask.); Carrot River basin (Sask.); Red River above Winnipeg (Man.) (refer to Section 4.3.8.3).

e) Contributions To Flooding By Urban Development:

1. Impervious surfaces and storm sewers:

When impervious surfaces such as roads, roofs, industrial and commercial areas, parking lots, airports and storm sewer systems conduct precipitation rapidly into the mainstream, total and peak flows are both increased (refer to Section 4.3.8.4).

2. Urban encroachment onto the flood plain:

When urban structures impede and deflect the flow of flood waters further away from the river, the flood period can be prolonged, flooding can occur in areas which would not normally flood under similar circumstances, and the flood damage can be increased. Example: Calgary, Alberta -- Bow and Elbow Rivers; Many other urban centers located on the flood plain such as Winnipeg (Man.), Lower Mainland near Vancouver (B.C.), and others (refer to Section 4.3.8.4).

IX. Interbasin Transfers:

a) Water Diversion:

Where a water diversion adds more water to a river channel than that channel (or a receiving area downstream) is capable of carrying, localized flooding can occur. Examples: Portage Diversion; St. Mary's River to Milk River Diversion; Mud Lake to Smuts Creek Diversion. Also common in irrigation areas where "return flow" greatly exceeds the capacity of local stream channels, for example, various coulees in Eastern Irrigation District.

4.3 Discussion - The Flood Causal Factors:

To better understand the flood causal factors and the factors which contribute to variations in flood intensity (presented in Table 4.2), further clarification, delineation and discussion are necessary. In the following section, case studies have been used to indicate the nature and extent of most of the current flood causal factors in Western Canada. Many of the flood causal factors, however, have been inadequately documented in the study area, and world and/or hypothetical examples have often been included.

The recurrence frequencies of many of the flood causal factors in the classification vary considerably. For many causal factors, the recurrence frequencies have not been calculated due to the rare nature of the flood event. For example, the frequency of a severe flood from a landslide-created wave surge (causal factor V and VIII.c.2&3) at a specific location is very difficult to determine. An event of this type may not have occurred during the period of record, and therefore, it is almost impossible to accurately determine a return frequency (Laycock, personal communication, Nov. 1980). An attempt, however, has been made in the following discussion to estimate very general recurrence frequencies for several of the causal factors in the classification. In most cases an actual frequency value has not been provided, only an indication of whether the frequency is high, medium or low. In certain case studies, particularly for river flooding, frequency figures will be included where relevant.

The patterns of occurrence, which have been mapped for the major flood causal factors, were difficult, and in many cases, impossible to determine accurately. Government flood reports, personal communications, newspaper and published research projects were used to establish specific flood locations, but in most cases the results were generalized. This indicates that only limited research has been conducted on many of the causal factors in Western Canada, and that possibly many flood management decisions are based on limited information. The shortage of data on flood causal factors has reduced both the accuracy and usefulness of the maps. The maps (Figures 4.1 to 4.5), however, do provide a general indication of the potential

extent of the flood hazard in Western Canada.

An attempt has been made to link several of the major causal factors to possible applications in flood loss reduction management. A range of the potential adjustments are presented in Table 4.3 which has been taken from research conducted by Staite (1979). Description and analyses of the various components presented in Table 4.3 have been reviewed by numerous researchers (e.g. Burton et al., 1968; Mitchell et al., 1978; Saarinen, 1974; Staite, 1979) and therefore will not be re-examined here.

4.3.1 Natural Channel Blockage (I):

4.3.1.1 Ice Jams (I.a):

In many regions of Western Canada, ice jam formation and flooding occur quite frequently. Natural conditions and man's interaction with the environment can both result in ice jam formation. These two factors are not necessarily mutually exclusive and can combine to create suitable conditions for ice jam formation. Naturally formed ice jams can be subdivided into those resulting from; 1) upstream ice break-up, 2) massive ice slabs grounding on the river bed, 3) the constriction of the river channel, 4) river gradient changes, 5) lake outflow into a frozen river channel, and 6) winter press-out from a lake. While the first four usually occur after spring break-up has progressed to varying stages, the last two usually occur during the winter. The locations of many of the ice jams which have been documented in Western Canada are presented in Figure 4.1 (n.b., in most locations the name of the townsite has been used for reference purposes).

Ice jams which result from man's activities can be initiated both naturally and unnaturally. River ice which breaks up by natural means can jam when it encounters bridges, roads, landfill and other man-made obstructions in the river channel. Unnatural break-up and jamming often occurs when water is released from a dam during the winter. This latter form of ice jam can interact with man's activities and cause substantial flooding. Spring runoff may be earlier and/or

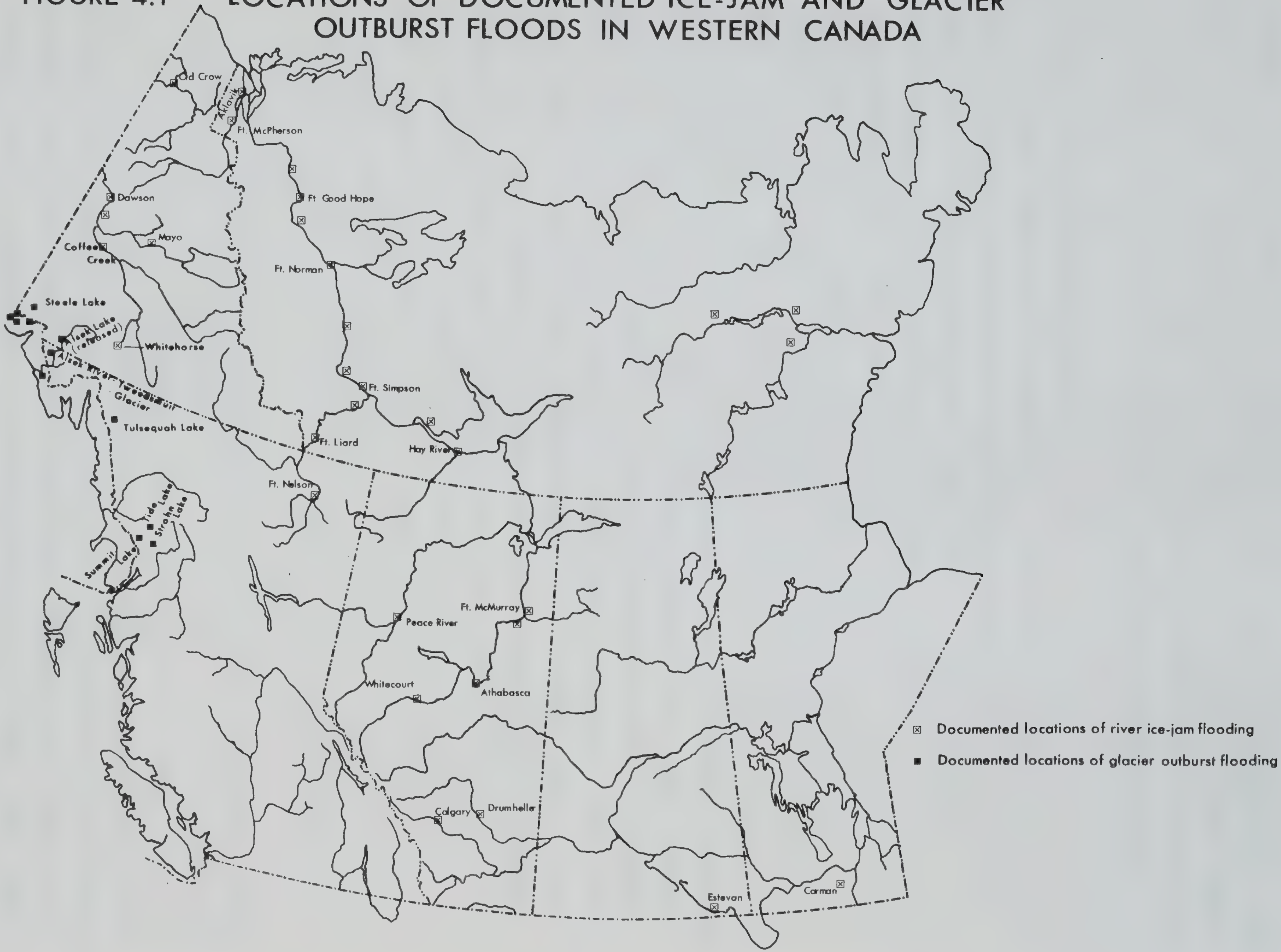
TABLE 4.3

THEORETICAL RANGE OF ADJUSTMENTS TO THE FLOOD HAZARD

MODIFY THE CAUSE	MODIFY THE HAZARD	MODIFY THE LOSS POTENTIAL	ADJUST TO THE LOSS		
			Spread the Loss	Plan for the Loss	Bear the Loss
watershed management	reservoirs	flood forecasting	subsidized insurance	private insurance	individual loss bearing
weather modification	dykes	flood proofing	public relief	reschedule production	
	channelization	emergency action	tax adjustments		
		land use management	public purchase		
		permanent evacuation			
		development policies			
		warning signs			
		public education			

Source: M. Staite, 1979 (Adapted with modifications from: I. Burton et al., 1968; T.F. Saarinen, 1974; B. Mitchell et al., 1978).

FIGURE 4.1 LOCATIONS OF DOCUMENTED ICE-JAM AND GLACIER OUTBURST FLOODS IN WESTERN CANADA



larger as a result of man's activities (e.g. urbanization, land clearing for agriculture, etc.) and this may add to flood damage in the still frozen north. The following discussion is an elaboration of the various types of ice jams, both natural and man influenced.

a) Upstream Ice Break-up (I.a.1):

It was explained in Chapter II that during early April, mild maritime polar air masses (mP) often move inland across the Cordillera and into the southern prairies. This warm air mass initiates spring break-up of the river ice in the southern portions of the northern river basins, but cold polar air still dominates the north and the river ice there remains solid. As warm temperatures gradually move northward, the river ice continues to break-up and flow northward. When the broken ice encounters the still frozen northern river ice, however, major ice jams can occur causing severe flooding. Locations where this type of flooding could potentially occur are generally found on rivers where there are no major lakes to stop ice movement. Many northward flowing rivers including the Athabasca, Hay, Yukon, Liard and portions of the MacKenzie River are common sites for this type of ice jam flooding. For example, ice jams have caused significant flooding at Whitecourt, Alberta seven times since 1929. The town is situated at the confluence of the McLeod and Athabasca Rivers, and in most years the ice on the McLeod breaks up first. The free ice jams against the solid ice on the Athabasca River, flooding the lower portion of Whitecourt, which is partially situated on the flood plain.

This type of ice jam flooding also occurs at Dawson, Yukon Territory, which is located at the junction of the Klondike and Yukon Rivers. On the average, the Klondike River breaks up five days before the Yukon River (this varied from one to eleven days between 1956 and 1973; Fenco, 1974, p.19). This lag time between break-ups on the Klondike and Yukon Rivers has caused static ice jams to form at the mouth of the Klondike River in 1959, 1963, 1966, and 1968. In early May 1979, an ice jam on the Yukon River caused severe flooding in Dawson City. Environment Canada (1981, p.vii)

report that;

> "Virtually the whole town was flooded when water levels on early May 3rd exceeded previously recorded heights. The dyke protecting the town was over-topped by as much as one metre."

Fort Simpson is located just downstream from the confluence of the Liard and Mackenzie Rivers. The Mackenzie River, however, does not break-up in a simple south to north progression. MacKay (1960) and MacKay and MacKay (1973a) state that break-up along the Mackenzie is neither continuous nor sequential from south to north because of the controlling influence of Great Slave Lake. The first major break-up on the Mackenzie River generally occurs at the junction of the Mackenzie and Liard Rivers. Henock (1973, p.169) states that recorded dates indicate that on the average, break-up occurs on the Liard River (May 18) eight days prior to break-up on the Mackenzie River (May 26). During the break-up period, the flow contribution of the Liard River to the Mackenzie River is more than half the total Mackenzie flow at Fort Simpson (MacKay and MacKay, 1973b. p.247). Tremendous pressures are exerted against the river ice along this point of the Mackenzie and differential heaving of the ice often produces major ice jams. Flooding in Fort Simpson has occurred fairly recently in 1963 and 1972. Historical and physical evidence indicates that the Fort Simpson town site has been flooded at other times in the past (MacKay and MacKay, 1973b, pp.239 and 247).

After the initial break-up on the Mackenzie River from Fort Simpson to Fort Good Hope, the river section from Fort Providence to Fort Simpson usually follows. Break-up on the section downstream from Fort Good Hope is often delayed because of its more northerly location, ice jams upstream, and the absence of major tributaries (MacKay and MacKay, 1973a, p.228).

b) Grounded River Slab Ice (I.a.2):

A second type of ice jam occurs when masses of slab ice ground on river bars, flood plain delta locations and/or other obstacles. The following description is taken from Walter Henry after he observed the break-up on the Yukon River in 1965. Henry (1965, pp.82-83) suggests that when the spring thaw arrives, the snow melts from

the river banks several days before break-up begins. The ice next to the bank then melts and open water flows between the bank and the ice pack. The ice in the middle of the Yukon River has not thawed yet and may begin to move downstream in sheets which can exceed 400 metres in length and 60 metres in width. These sheets quickly break-down into ice pans approximately 9-12 metres in length and about 1.5 metres thick. The ice pans often ground on sand bars or other river obstacles and fuse together as more ice accumulates. Eventually, ice dams the river completely and the water level rises.

This form of ice jam is fairly common and occurs on many rivers in the Northwest Territories, Yukon Territory and in the northern portions of Alberta and Saskatchewan (Doyle, 1977; Gerard, 1974; Grey, 1977; Jasper, 1980; MacKay and MacKay, 1973b; Osborn et al., 1975). The Town of Hay River, for example, which is located at the mouth of the Hay River where it empties into Great Slave Lake, has experienced significant flooding from this form of ice jamming. The ice flows which cause the jams originate from the river sections just upstream from Hay River. In 1963 a major jam resulted in the flooding of much of Vale Island, where the airport and the older part of the town are situated. In 1974 another major ice jam flood occurred on the Hay River causing several millions of dollars damage. Jasper (personal communication, 1980) states that the ice responsible for the ice jam floods in Hay River originate on the lower 18-24 kilometres of the Hay River as two waterfalls of 10 and 25 metres crush the river ice which flows northward from Alberta. Hay River also experiences ice jams when the river ice piles up behind the still frozen ice on Great Slave Lake. Therefore, the fact that Hay River is a northward flowing river, and ice on the southern portion would melt first appears not to be responsible for the formation of any ice jams.

The potential for grounded ice sheets and subsequent ice jam formation and flooding appears to be a major problem along the Mackenzie River. MacKay and MacKay (1973b, pp.256-257) determined that of the twenty-two potentially hazardous ice jam locations along the Mackenzie River, shoals were located at fourteen sites. Two centers, Fort Simpson and Fort Norman (located at the confluence of the Great

Bear and Mackenzie Rivers), were included in these flood sites. Miles (1981) reports that portions of the Murray River, which runs through British Columbia's Northeast Coal region, are subject to frazil ice generation and the formation of hanging ice dams where large ice sheets ground in shallows.

c) Natural Channel Constrictions (I.a.3 and VII.b.2):

Ice jams can occur at points along a river channel which are narrow and constricted. Fenco (1974, p.20) suggests that sharp narrow river bends are the most common location for jams of this type to form. For example, downstream from Dawson, Yukon Territory, there are two locations where ice jams of this type commonly form. At both locations, Cassiar Creek (24 kilometres downstream) and Rotten Creek (5 kilometres downstream), sharp bends in the river act as ice catchments. While ice jams frequently form at these two locations, flood conditions have only occurred a few times at Dawson.

Channel constrictions also appear to be a problem on the Kazan, Thelon and Mackenzie Rivers. When reporting on a proposed pipeline route, which passed through the Thelon-Kazan River basin in the Keewatin District in the Northwest Territories, B.J. Grey (1977, p.12) noted that both rivers have extensive sections bounded by boulder ridges or ramparts. These locations are apparently favorable to the formation of ice jams, and as the river flow in the Thelon and Kazan basins is generally from southwest to northeast, the potential for this event is high. Grey (1977, p.1) states that "due to the large size of these river basins, and the existence of large lake sections, break-up is not instantaneous throughout." River ice break-up can occur in the southern portion of the basin more than a month before such events occur at the outlet of the Thelon River (Hudson Bay).

As was explained earlier, MacKay and MacKay (1973b) have thoroughly documented the locations of potential and known ice jam formations along the Mackenzie River from Great Slave Lake north to the Beaufort Sea. Of the twenty-two potential ice jam sites identified, eleven are recognized as channel constriction locations. MacKay

and MacKay (1973b, p.251) state:

> "One characteristic of the majority of Mackenzie River ice jam locations is the constriction of the channel. The mean widths at jams is 1.3 km (0.81 miles) as compared to the mean width of the Mackenzie River as measured at 16 km (10 mile) intervals of 2.6 km (1.36 miles). In fact, only two of twenty-two jam locations exceed the mean width of the river. One of these is Berry Island, where a narrow deep-water channel deflects east past the face of the island and where the channel to the west is island-strewn with shoal areas. The other is at the junction of the Great Bear with the Mackenzie River, where shoals off the tributary mouth in conjunction with Windy Island, Great Bear Rock and the ice cover of both rivers often cause ice jamming."

One potentially hazardous site noted by MacKay and MacKay lies below the Ramparts at the old Fort Good Hope settlement located on Manitou Island. The Ramparts are a very constricted 11 km long section of the Mackenzie which cuts through perpendicular limestone cliffs. Here the river channel narrows from 5 km wide to 0.4 km at the entrance. Ice jams are a regular occurrence here and the ice dammed water shows evidence of flooding at 14 metres above datum. The old town site was completely destroyed in the spring of 1836 following the disintegration of an ice jam in the Ramparts.

In the many sources reviewed by the author there were often only general references to this type of ice jam. It is difficult, therefore, to suggest how common this type of ice jam is, and what the distribution pattern would be.

d) River Gradient Changes (I.1.4):

Ice jams can occur at particular locations of a river where the gradient of that river substantially decreases. Rivers in Western Canada with potential for this type of ice jam flooding are generally located east of the Cordillera with headwaters in the upper regions of the Canadian Shield or Rocky Mountains. The Kazan, Hay, Peace, Nelson and Athabasca Rivers all have substantial gradient changes at various points and ice jam floods have been documented on several of these (see below). There is potential for ice jams of this variety on many other rivers in Western Canada but further study would be required to identify specific locations. The locations of Fort McMurray, Alberta, which is situated at the confluence of the Athabasca

and Clearwater Rivers provides an excellent example of this type of ice jam flooding. Spring break-up usually occurs upstream of Fort McMurray between early April and early May. In many years ice jams initially form on the many rapids 10-30 kilometres upstream from the town. Eventually, these ice jams fail, sending large amounts of ice downstream. Just downstream from Fort McMurray the gradient of the Athabasca River becomes markedly flatter and the channel becomes wider and shallower. Here the average velocity of the river decreases and the channel contains numerous islands (Doyle, 1977b, p.11). The river ice from upstream frequently jams when it reaches this stretch of the Athabasca River. Doyle (1977a, p.9) states that because of the nature of the river channel at Fort McMurray, the proximity of this stretch of river to the rapids, and the fact that the Athabasca River is a northward flowing river (differential ice break-up dates), the probability of ice jams occurring during future break-up is high. The severity of future jams will depend on many factors such as location, mode of failure of jams upstream from Fort McMurray, size, what action is taken by man, and the discharge and ice conditions on the Athabasca and Clearwater Rivers at the time of break-up.

The previous discussion is only a description of the process by which ice jams occur at Fort McMurray. Many of these ice jams have caused extensive flooding in the townsite. In 1977, for example, serious flooding resulted when a large volume of ice, which was released by an ice jam upstream of Fort McMurray, grounded in the shallows in the vicinity of the mouth of the Clearwater. Flow from the Clearwater River was unable to discharge into the Athabasca River, and the ice jam directed a portion of the Athabasca's flow into the Clearwater. This, combined with the unusual length and persistence of the ice jams, caused extensive flooding to occur in the townsite. Damage from the 1977 flood was approximately $2.6 million (McMann, 1979, p.10).

e) Lake Over-flow Into A Frozen Channel (I.a.5):

Ice jams can occur on ice-bound creeks which are located downstream

from an unfrozen lake. During the river and lake freeze-up period, it is not uncommon for creeks and streams to freeze first. When a lake-fed stream is frozen over, it is possible for the lake to continue discharging if a sufficient head or lake level is still present. If the flow velocity from the lake is large enough, the river ice can break-up and jam downstream causing localized flooding. Laycock (personal communication, January 1981) suggests that this situation occurs in Baker Creek basin which is located just north of Yellowknife, N.W.T. Baker Creek usually freezes before Baker Lake, and if sufficient head is still present in Baker Lake, it is possible for break-up and ice jamming to occur on Baker Creek. Ice jamming of this type is mostly a problem in the north but could occur in some lakes further south.

f) Winter Press-out From A Lake (I.a.6 and VI.c):

It is possible for a "delayed ice jam" to form during the winter on a lake-fed stream. If snow falls on a lake, after the lake and drainage system are frozen over, loading can press water out of the lake and into the frozen stream channel. As the lake water flows down the then ice constricted channel, the extra volume spreads out from the channel and freezes up. If sufficient press-out occurs, the water can run over the stream banks and flood onto the flood plain (where it freezes). In the spring when break-up occurs, this solid mass is slow to melt and jamming can result. Laycock (personal communication, January 1981) suggests that this has occurred on Baker Creek north of Yellowknife. Ice and snow on the lake squeeze freezing water out of the lake and down Baker Creek. Ice accumulation on the flood plain has been up to 1.5 metres thick, and has caused localized flooding during the press-out and snowmelt periods. Laycock (personal communication, March 1981) suggests that spring snowmelt waters may also cause flooding before a channel has been re-established in this ice. It is anticipated that ice jams caused by winter press-out from a lake occur predominantly in the northern regions of Western Canada. Miles (1981) suggests that this can be a serious problem in northern British Columbia.

g) Ice Jams Associated With The Activities Of Man (VII.a.1 and VII.c.1):

Engineered structures along or across a river channel can often cause ice jams to form. Winter release of water from power dam reservoirs, for example, have caused many serious ice jam floods on certain rivers in Western Canada. The Town of Mayo in the Yukon Territory has been subject to ice jam flooding during the winter since a power dam was completed upstream in 1956. Releases from the reservoir break-up the solid river ice which then flows downstream where it jams at the confluence of the Mayo and Stewart Rivers. In 1957 a dyke was constructed in Mayo after ice jams caused a flash flood at the townsite. The dyke successfully protected the town until 1964 when flood waters caused the dyke to collapse. Fenco (1974, Appendix III, pp.7-8) states that ice jam floods have continued to occur in Mayo since that time.

Similarly, many ice jams on the Peace River have been caused by winter release from the Bennett Dam reservoir. Since the completion of the dam in 1967, power production discharges have increased winter flows on the Peace River from approximately 424 m^3/s to 1698 m^3/s. The drastic fluctuation of discharge levels has been responsible for ice jam flooding at many communities on the Peace River. For example, in 1973, the town of Peace River experienced a severe flood threat when an ice jam which formed downstream raised the water level approximately 7 metres above normal. Dykes which had been constructed after the 1972 spring rain floods prevented the town from being inundated, however.

Man-made bridges can also result in ice jam flooding (causal factor VIII.a.1). Many bridges, particularly the older ones, are constructed with one or more bridge supports located in the river channel. During break-up these piers can obstruct the flow of river ice, and subsequently, jams can form. Furthermore, when the bridge is low to the river level, it can assist in the formation of the jam by actually becoming part of it. The water and ice backs up behind the jam and severe localized flooding can result. Doyle and Anderson (1978, p.11) state that the MacEwan Bridge at Fort McMurray was the cause of a 1978 ice jam. The river gradient at this point

is very low and the river velocity was not capable of pushing the ice under the bridge. Ice piled up against the three bridge piers in the center of the channel, and some flooding was experienced in the town. Fenco (1974, Appendix VI, p.16) states that the McQuesten Bridge, which is located on the Stewart Crossing - Dawson Road in the Yukon, was destroyed by an ice jam in 1961. Later that same year the McQuesten Bridge was re-built with a 70 metre pier-free span in the center.

Another type of ice jam can occur where man has constricted the river channel with landfill and/or dykes (causal factor VII.b). The Montreal Engineering Company (1969, p.9) states that the north channel of the Bow River beside St. Georges Island in Calgary is subject to winter ice jams because of the channel encroachment by filling and dyking. Maximum observed stage rises have been 3.6 metres. In 1975, an ice jam occurred opposite St. Georges Island and emergency measures were required to prevent flooding. Flooding of this type occurred frequently in Calgary before Bearspaw Dam was constructed due to power demand surges from Ghost Dam.

h) Management Alternatives:

In the preceding discussion it is apparent that various types of ice jams have caused flooding in many regions of Western Canada. There are, however, a wide range of flood reduction management alternatives available which essentially come under the categories of "modifying the hazard" and "modifying the loss potential" (Table 4.3). Initially, basic site evaluation data would be required including determination of the time period for ice jam occurrence, potential type of ice jam formation, potential elevations of water at various discharge rates and ice jam sizes, and upstream and downstream areas expected to flood. Once this information has been collected the planner could then determine a flood damage reduction management strategy. This strategy could be based on a combination of engineered flood control structures (e.g., dykes, channelization, flow diversion) and other measures designed to reduce flood losses (e.g., flood forecasting, flood proofing, land use management, permanent evacuation,

public education, etc.). Certain management alternatives, however, may be impractical or difficult to implement in some situations. For example, the town of Old Crow, which is located on the Porcupine River in Yukon Territory, has experienced severe ice jam flooding in 1964, 1965, 1971, 1973 and 1980 (Fenco 1974, Orecklin personal communication 1980). Fenco (1974, p.80) reports that only emergency measures such as sand bagging and evacuation can be taken to protect the town because the flat terrain surrounding the town site essentially prohibits the construction of any economically feasible flood control structures.

4.3.1.2 Glacier Activities (I.b):

a) Glacier-Dammed Lakes and Outburst Floods (I.b.1):

In Western Canada, glacier-dammed lakes are generally located along the Coast Range of British Columbia and in the mountains of the southwest corner of the Yukon Territory. The locations of several of the better studied glacier-dammed lakes are indicated in Figure 4.1. Collins and Clarke (1977, p.218) suggest that there are probably more than 200 ice-dammed basins in the Yukon portion of the St. Elias Mountain Range alone. In the Coast Range of British Columbia, there are also many glacier-dammed lakes, but the density per unit area is much lower than in the Yukon. Stone (1963b, p.333) has identified the locations of numerous ice-dammed lakes in Alaska and several of these have been included in Figure 4.1.

Ice-dammed lakes can be formed in a number of ways. The most common type occurs where a lake is impounded in an ice-free tributary valley at the side of a major valley glacier. The lakes can vary in size, but are usually small and are located adjacent to the lower reaches of the glacier. Two examples of this type of lake are Summit Lake and Tulsequah Lake, both in British Columbia (Figure 4.1). Marcus (1960) has observed and documented the release of Tulsequah Lake, and his work is substantiated by Stone (1963b).

Occasionally, lakes are formed when an ice free valley is blocked by the advance of a glacier from a tributary valley. In

this situation very large lakes can form. For example, in the Yukon a lake was formed about 200 years ago when the Alsek River was dammed by the advancing Lowell Glacier which has since retreated. The Alsek River is once again being threatened by the Tweedsmuir Glacier in northwest British Columbia (Figure 4.1).

Ice-dammed lakes can occur where two glaciers converge or when a surface area of a glacier collapses, forming a sink hole. Young (1977, pp.3-4) provides examples of these types of ice-dammed lakes in Iceland and on Axel Heiberg Island in the N.W.T. Maag (1969) has also conducted extensive research on the various types of ice-dammed lakes on Axel Heiburg Island.

The hazardous element of an ice-dammed lake is the catastrophic flooding which can occur when it releases. The lakes can empty and refill many times during the period they exist. Usually the lakes drain through, underneath, or over the ice. Unfortunately, there is presently no predictive method available to determine when the lakes will release, and draining can occur any time of the year.

Water released from the ice-dammed lake can cause significant and damaging floods. Wood (1972, p.5) states that Steele Creek basin in the Yukon Territories has for many years been considered a forbidden valley by local Indians who feared "annihilation from flood water and crashing ice" when the dammed lake suddenly released.

In October 1958, October 1960, October 1961, and August 1962, Strohn Lake in northwest British Columbia (Figure 4.1) released suddenly and caused considerable damage to the highway between Stewart and Bear River Pass. Despite controlled lake drainage attempts by the British Columbia Department of Highways, Strohn Lake continues to fill and release.

Summit Lake which is dammed by Salmon Glacier just north of Stewart, B.C., flooded and refilled six times between 1957 and 1970 (Figure 4.1). The 1957 flood caused extensive damage to roads, bridges and mining communities in the Salmon River basin and Matthews (1965, p.50) estimates that the damages exceeded $200,000 (1957 dollars).

Approximately 200 years ago Lowell Glacier impounded a lake 84 kilometres long when it surged across the Alsek River in the

Yukon. In the Alsek River Valley, evidence has been located which indicates the scale of the floods which occurred when these massive ice-dammed lakes on the Alsek River released. Environment Canada (1975, p.72) reports that, "scoured valley walls, giant ripple marks on outwash deposits, and sparse, youthful vegetation in the lowland areas provides spectacular evidence of the passage of gigantic floods down the Alsek valley to the sea."

Floods from ice-dammed lakes can be severe and catastrophic as an individual event, but if the release coincides with another flood event or conditions in the watershed are already conducive to flooding, the flood hazard can be drastically increased. Because the lake release can occur at any time of year, the possibility exists that the release could coincide with the high yields from spring snowmelt or with the runoff from a major rain storm (or both). Young (1977, p.6) also suggests that when there are many ice-dammed lakes within a single watershed, two or more lakes could release simultaneously, or a higher elevation lake could release into a lower elevation lake causing the latter to release. Young also suggests that a winter release can be sufficient to break the river ice downstream which can cause ice jams to occur. The probabilities of these events occurring, while unknown at this time, would likely be very low.

Chow (1964, p.16-30) reports that in August, 1959, a glacier dam burst in a remote mountain valley in the Karakoram Range in Kashmir and caused a flood rise of more than 30 metres at a distance of over 40 kilometres from the point of outburst. While the areas in Western Canada where these glacier release floods occur are relatively unpopulated, the flood hazard could create severe problems as man moves into these regions to develop the resource potential. Therefore to reduce the potential interaction between man's activities and the sudden release from ice-dammed lakes, studies to locate these lakes, determine the drainage pattern and frequency of release should be conducted prior to development in these areas. This knowledge would help planners to determine whether or not special flood control structures were warranted and would help engineers design roads,

bridges and culverts.

4.3.1.3 Landslides - River Blockage (I.c.1):

Landslides can be triggered by many factors including river bank erosion, dilatation, weathering and earthquakes. If a landslide were to block a river valley, the impounded waters could form a lake and/or cause flooding both upstream and downstream. For example, if a large slide the magnitude of the Frank Slide in southern Alberta or the Hope-Princeton Slide in southwestern British Columbia were to block a river channel downstream from an urban community, the results would be similar to an ice jam flood. The water could back up and cause flooding in local communities. If it were to overflow, the lake could suddenly drain, producing significant flooding downstream (Chow, 1964, pp.23-24).

The probability of this type of flooding occurring at any one location in Western Canada would have to be considered low. The only locations where a slide of sufficient magnitude could occur would be in the Cordillera region of British Columbia, the Yukon, Alberta and parts of the Northwest Territories. Laycock (personal communication, March 1980) suggests that significant landslides on both the Peace and Fraser Rivers in British Columbia have been reported within the past 20 years, but in neither case was there major or long-term flooding. Cruden (1976) has attempted to identify many of the major rock slides in the Rocky Mountains.

In 1979 a major slide occurred in northwest British Columbia on the Inklin River (a tributary of the Taku River) creating a 20 kilometre long lake which was approximately 90 metres deep. The British Columbia Ministry of Environment expressed concern that it might suddenly release, but fortunately the water over-topped and slowly eroded the slide resulting in a gradual release of the lake (Simmons, personal communication, April 1982).

Recently, however, a landslide in the Snoqualmie pass, which is located in the Cascade Mountain Range in Washington State, caused substantial localized flooding. On January 25, 1982, after heavy rain and wet snow battered the west coast region of both British

Columbia and Washington, a debris slide blocked a creek in the pass. Before the problem was discovered, the creek backed up behind the slide and forced the dam to burst sending a wall of water over 6 metres high rushing down the creek channel. There was some damage to the highway system, but no other significant damage was reported. The potential for major flood damage, however, is quite evident if a situation such as this were to occur above an urban center.

Perhaps the most effective method of planning with respect to landslides is to know where the potential exists for such an event. Terrain inventory and geological hazard identification and location studies such as the one conducted by Howes (1981), would provide the planner with detailed information and quick reference to the drainage basins where landslides and avalanches could provide a potential threat to development. Conversely, a mapped inventory of the geological hazards would also identify "safe" areas. Other alternatives available to the planner are to make emergency organizations aware of the potential from this and other types of sudden flooding so that they can be better prepared to evacuate people. Other potential alternatives are listed in Table 4.3.

4.3.1.4 Vegetation Constriction of the River Channel (I.d):

Vegetation constriction of a river channel can contribute to flooding during the high yield periods. The vegetation, whether in the river channel or on the flood plain, can cause a flow lag which helps to back up water in the river channel. If a river floods its banks, vegetation bordering the channel can deflect the water outwards across the flood plain and cause more serious flooding to occur than would normally have been expected. When reporting on the Calgary flood problem, the Montreal Engineering Company (1968, p.30) suggested that vegetation in the Bow and Elbow River channels and the low level bushes and trees along the river banks should be removed so that high flows would not be impeded.

On many smaller streams in northern Canada, muskeg development has impeded and backed up flow. This is a serious problem in low flow years as muskeg can sufficiently block the stream channel so

that during wet years the channel is too constricted to carry the flows (Laycock, personal communication, March 1981). This is also true of some lake outlets. For example, in the early 1970's, after a period of dry years (lake level dropped), the outlet from Sylvan Lake became clogged up by vegetation and debris. When the lake level eventually rose again, shore line flooding occurred when the lake could not adequately discharge into the stream channel. In the spring of 1982 shore line flooding was experienced on Vaseux Lake in southern British Columbia when Eurasian Milfoil weed plugged-up the discharge channel at the south end of the lake.

If planners are aware of this problem steps can be taken to clear the land (drainage channels) of any new growth during the dry period. If underwater weed was causing the problem any one of a number of weed harvesting techniques could be used.

Unfortunately, this flood causal factor is associated with many major rivers in Western Canada. This makes it very difficult to establish accurately the occurrence pattern for it.

4.3.1.5 Sediment Deposition (I.e):

a) River Bed Deposits (I.e.1):

Sediment which has been deposited in the river channel is not generally considered to be a principal flood causal factor, but rather a contributing factor. When a river channel becomes heavily covered by sediment deposits, such as sand bars, the capacity of the river channel is reduced. Therefore, when a high stage is experienced, the possibility of flooding increases due to the reduction in river channel capacity. For example, the Bow River through Calgary has large sand and gravel bars located in the channel. If these sand bars were removed, the capacity of the Bow River would be increased and flooding would not occur as frequently at lower stages (Montreal Engineering Report, 1963, p.5).

This flood causal factor most commonly occurs where streams flow out of the mountains and foothills and onto flatter plains. While it is difficult to identify all the regions of Western Canada

where this occurs, it is possible to identify particular rivers and locations where river sediments do significantly contribute to flooding. These include; the Bow River in Calgary, the Red Deer River near Sundre, the Swan River at Lesser Slave Lake, the Paddle River, various creeks near Dauphin, Manitoba which rise on Riding Mountain, and the Fraser River from Hope downstream.

b) Deposition at River-Lake Junctions (I.e.2):

Sediment deposition at the point where a river discharges into a lake can cause a river to "back-up" during high discharge periods. The Swan River, which flows northward into Lesser Slave Lake in Alberta, provides an excellent example of this form of flooding.

In 1957, oil exploration and development companies began to open up the Swan Hills watershed. Since then, grids of roads, well sites, batteries, pipelines and gas lines have been constructed in the basin. All this activity and development has resulted in a major erosion problem in the Swan Hills area. The deforestation of approximately 15 to 18 percent of the area and the removal of most of the thin layer of soil cover triggered a major erosion problem (Lengelle, 1976, p.2). Much of this eroded material has worked its way into the Swan River and has eventually ended up in Lesser Slave Lake. Lengelle (1976, p.3) suggests that up to 50,000 tons of silt per day is being carried by the Swan River, and that a subacquatic delta is forming at the mouth of the river at a rate of 0.8 kilometres per year.

In a 1971 report to the Government of Alberta on the flooding on the Swan River, Ruste (then Minister of Agriculture) and Henderson (then Minister of Environment) state;

> "The current 1971 series of floods have been the most serious in memory with three floodings of some farms in the space of fourteen days. There was also a marked change in the pattern of flooding...since water levels in the southern end of the settlement of Kinuso were two to three feet lower than in 1961 and flooding intensified nearer to the mouth of the river, we are of the opinion that serious silting of the river mouth has occurred during the past decades."

The flooding in 1971 was a response to rainfall runoff. Ruste and Henderson (1971, p.2) state, however;

> "that oil industry development in the Swan Hills is the prime cause of this recent flood of the Swan River. The numerous roads, cuts and clearing allow a greatly accelerated runoff. Excessive siltation occurs in the river which when deposited at the mouth of the river results in blockage of the flow."

A similar flood situation occurred on June 27, 1975.

The previous example has shown that this form of flooding can be caused by man's influence on the environment. Flooding of this type can also occur naturally from forest fires in mountain and hill-land watersheds, and from overgrazing. (The contributions to flooding by these causal factors will be discussed later in this chapter.)

c) Alluvial Fan Deposits (I.e.3):

An alluvial fan is a deposit of sediment laid down by a swift flowing stream as it enters a plain or a valley. Moore (1969, p.10) suggests that drier mountain regions are the most common location of alluvial fans because alternate low winter flows and high spring flood discharges of the mountain streams favor their formation. In the Cordillera region of Western Canada, urban development on alluvial fans has become a serious flood problem. Often the flows of the streams on the fan are flashy following a rainstorm, and because of the cone shape of the fan the stream frequently tends to alter its channel. When this occurs, many of the structures on the fan are seriously damaged. During the June 1964 flood in the Oldman River basin, when a major storm deposited over 250 mm of rain in this area, severe flooding occurred in the Waterton Park townsite, which is located on an alluvial fan. Cameron Creek, which flows across the alluvial fan, left the man-made channel and returned to other former courses. The flow on Cameron Creek was "flashy" and consequently significant damage was caused to houses, cars and other structures.

In British Columbia, urban developments on alluvial fans are also causing concern for the provincial government authorities. Several centers, including Golden and Bella Coola, are situated on fans which are prone to flooding. The B.C. Ministry of the Environment

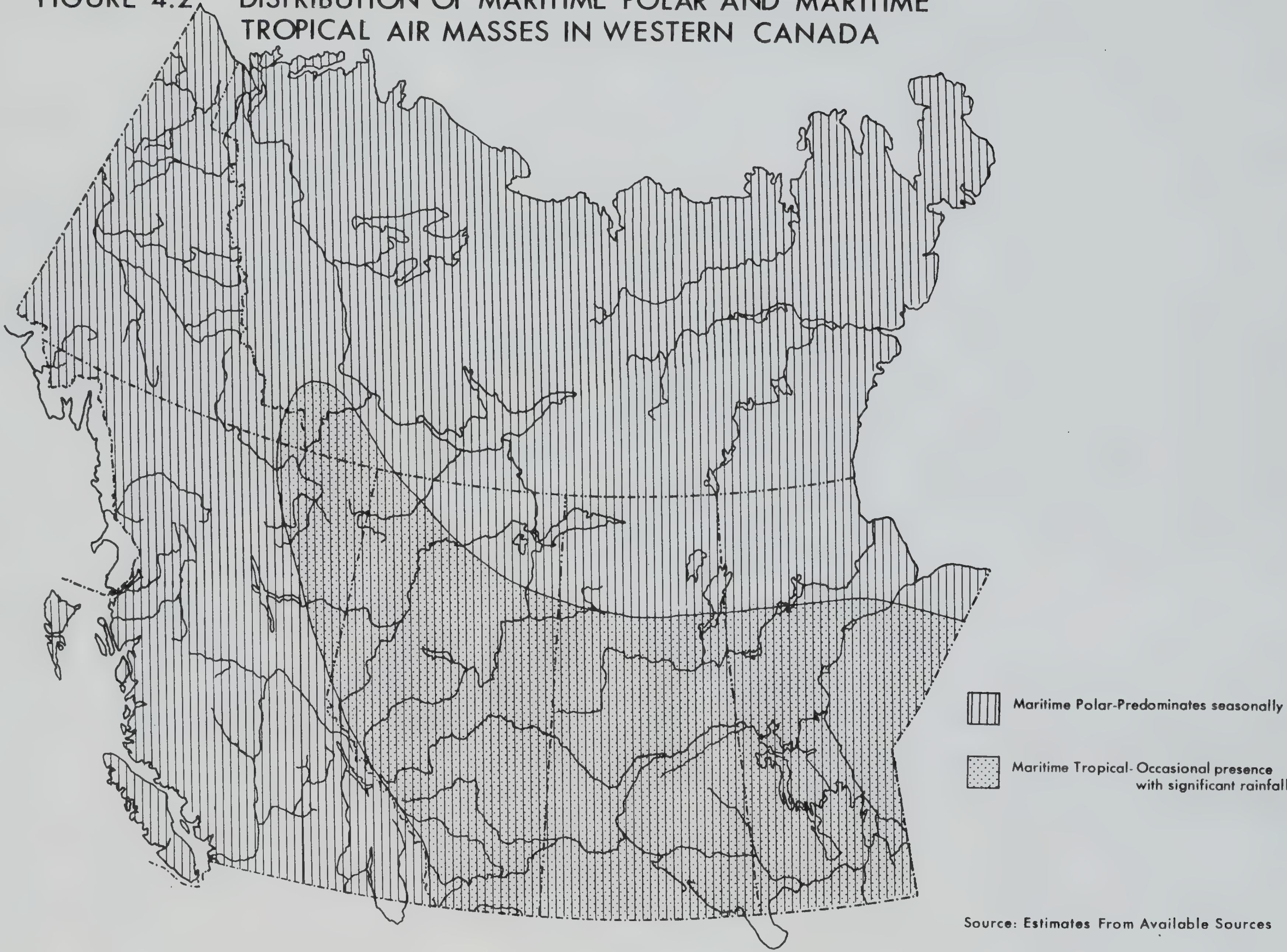
has taken steps to control development on the alluvial fans. It is no longer possible to build any new structures within a set flood zone running parallel to the stream channel. In Golden, all new structures must be constructed at least one metre above the road surface as the roads have been designed to act as floodways in the event that Holt Creek leaves its channel (Simmons, personal communication, September 1980). All other proposed structures must be approved by the Ministry of the Environment before construction and must be constructed at least one metre above the fan. Any structures which were originally constructed on the fan prior to the intervention by the Ministry of the Environment can remain.

4.3.2 Meteorological Factors (II):

4.3.2.1 Precipitation - Air Masses and Uplift Processes (II.a):

Not surprisingly, the author found that in studies which examined specific flood events, rainfall was usually identified as the principal causal factor. There are two major air masses which carry large amounts of moisture into Western Canada and produce most of the rainfall experienced in the region. These are, the maritime polar (mP) mass which moves eastward from the Pacific Ocean, and the maritime tropical (mT) air mass which flows northward from the Gulf of Mexico and the Atlantic Ocean. Figure 4.2 outlines the general areas of influence of these two air masses. In the following discussion, the characteristics of these two air masses will be described as they pertain to Western Canada. The author feels, however, that a limited discussion of the air masses will not sufficiently illustrate how and where heavy rainfall occurs in Western Canada. Therefore, a discussion of the uplift mechanisms which cause heavy precipitation is felt to be necessary. Where possible, studies will be used to illustrate each type. It should be noted that while most of the case studies will describe specific rainfall floods in the southern portion of the study area, this is only because many of the northern rainfall events have not been adequately documented. For example, the 1972 Arctic Red River flood was caused by a severe rainstorm,

FIGURE 4.2 DISTRIBUTION OF MARITIME POLAR AND MARITIME TROPICAL AIR MASSES IN WESTERN CANADA



Source: Estimates From Available Sources

but it has not been conclusively determined what combination of meteorological events caused the storm.

a) Air Masses:

i) Maritime Tropical (mT) Air Masses:

In late spring and early summer, large mT air masses provide much of the precipitation east of the Rocky Mountains in the southern portion of the prairies. The source regions of the mT air mass are the exceptionally warm ocean surfaces of the Gulf of Mexico, the Caribbean Sea and the subtropical western Atlantic. During the winter, polar air normally prevents the mT air masses from moving northward into Canada. In the summer, however, the mT air masses move northward releasing precipitation from the Atlantic to the Rockies. As was suggested in Chapter II, Laycock (1972, p.16) has estimated that the proportionate distribution of precipitation from mT air may be approximately 50 percent for Winnipeg, 25 percent for Medicine Hat, and 10 percent for Edmonton. This does not mean that mT air masses are not responsible for any precipitation flooding in Alberta. This precipitation is received in large amounts in relatively few major storms, and several major floods attributable to this air mass have occurred and will be reviewed later.

In Western Canada, mT air masses are most frequently present in the southeast plains, but the most intense storms occur in areas with orographic uplift added to warm front, convergence, or cold front activity (e.g., Turtle and Riding Mountain in the east and the Rocky Mountain front range and foothills in the west). Maritime tropical air masses are relatively low-level resulting in very little penetration into the Rockies. Severe eastern slope storms occur in approximately 1 of every 3 years and occurrence is partially a matter of chance (Thompson, 1976). North of Peace River mT-caused storms become increasingly rare.

Weber (1980, personal communication) suggests that in Manitoba, rain-generated floods can occur during the summer or early fall on medium size watersheds (up to 3,900 square kilometres in area)

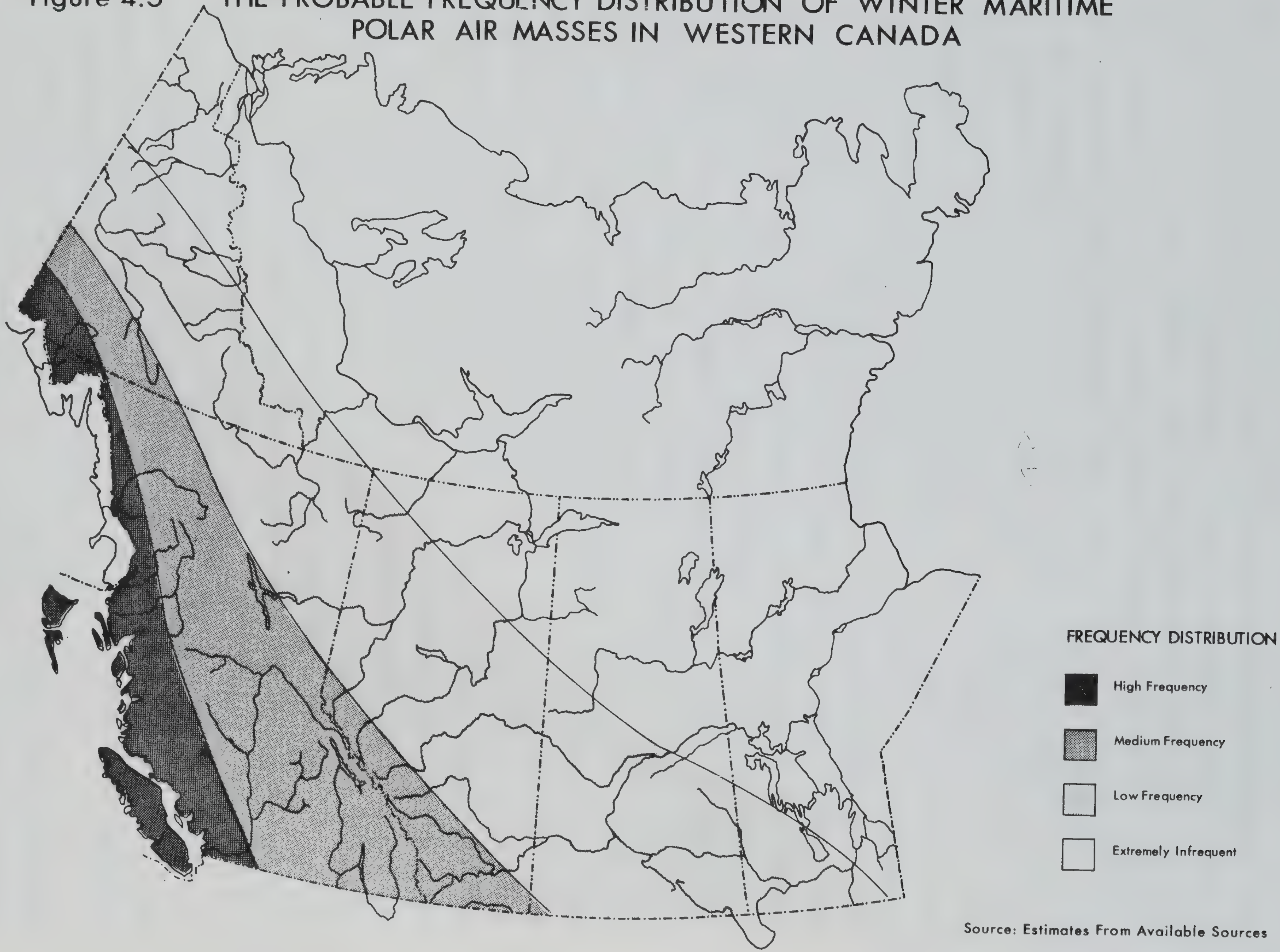
due to intense atmospheric disturbances involving mT air. Weber further states that rain-generated floods on large river systems such as the Red, Assiniboine, or Souris Rivers are extremely rare, but have occurred in the late spring when the soil was still saturated from snowmelt. Floods of this nature have occurred in late spring on the Assiniboine in 1954 and 1955, and on the Red River in 1950. This type of storm generated flood has also occurred on the eastern slopes of Alberta at Willow Creek in 1953, Waterton in 1964, and Smoky River in 1972 (Warner 1973, Warner and Thompson 1974).

The intense rain storms associated with mT air masses are difficult to forecast in advance, but when a storm does occur emergency measures organizations should anticipate that flooding could occur and issue the appropriate warnings. The occurrence frequency of mT rain storms is high enough for specific basins such as the Elbow and/or Bow Rivers that planning for flooding, particularly in June, should include allowance for these storms. If there is enough warning of a mT event occurring in the Eastern Slopes, reservoir levels could be quickly lowered, flood warnings issued and evacuation of people and property could be initiated. More long term planning is possible including development of reservoirs and catchment basins designed to handle sudden inflows, river channel diversions around population centers (Winnipeg), flood proofing, dyking and other flood damage reduction alternatives (see "Modify the Loss Potential", Table 4.3). Many other basic changes can be made to allow the passage of flood waters such as larger culvert sizes, bridges without piers in the river channel and restricting building encroachment onto the flood plain (Table 4.3).

ii) Maritime Polar (mP) Air Masses:

During late fall, winter and spring, mP air masses provide heavy precipitation to the west coast and interior of British Columbia. The mP air masses can also influence the winter, spring and summer climate on the southwestern portion of the prairies, principally southern Alberta. The probable frequency distribution of the winter mP air mass in Western Canada is illustrated in Figure 4.3. The

Figure 4.3 THE PROBABLE FREQUENCY DISTRIBUTION OF WINTER MARITIME POLAR AIR MASSES IN WESTERN CANADA



Source: Estimates From Available Sources

dark area along the coast region of British Columbia indicates that the mP air frequently dominates in this area. The gradual lighter bands to the east indicate that this domination decreases both as the distance from the Pacific Ocean increases and as the distance to the Arctic Ocean decreases. The source region of this air mass is the northern part of the Pacific Ocean, an area which in winter is dominated by the cyclonic circulations of the Aleutian Low. Most of the air that enters the mP source region originates in the cold continental areas to the north and west, and is drawn into the source region by the strong northwesterly flow converging on the Aleutian Low (Trewartha, 1968, p.180). Warmth and humidity from the ocean surface are added to the stable air, but as it becomes locked into the prevailing cyclonic circulation it is lifted. When the mP air air arrives on the coast of British Columbia it is relatively mild, with temperatures well above freezing. As this humid, unstable air mass is forced upwards over both the Coastal Mountain Range and the cooler air over land, rain falls in the lowlands and heavy snow can fall on the mountains. Trewartha (1968, p.180) explains that during the winter, as the maritime air continues inland over the successive mountain ranges the cold land lowers the air's surface temperature and condensation on the higher areas causes the low levels of the air mass to become drier. Therefore, by the time the air mass reaches Alberta, it is often transformed into a cold, dry, stable, continental air mass (although not as cold as those masses of continental origin). Where it makes contact with and over-runs colder air masses, however, some precipitation can occur (this will be discussed later in this section).

Laycock (1972, p.14) suggests that the greater part of the plains precipitation is associated with these mP air masses, and moisture releases can occur if strong uplift situations are present (cold front, summer convectional uplift, etc.)

The precipitation associated with mP air masses, while generally less intensive and localized than that associated with mT air masses, can cause extensive flooding along the coastal regions of British Columbia and under certain circumstances (mentioned above) on the

southern prairies. Unlike mT air masses, precipitation from mP air masses is easier to forecast in advance which allows for better preparation of emergency measures. People and livestock located in lowland areas subject to flooding can be warned and evacuated if required. For other management alternatives refer to the previous section and Table 4.3.

b) Uplift Processes:

i) Cold Fronts (II.a.1):

Heavy precipitation can occur along the leading edge of a cold air mass when the cold front acts like a wedge forcing the warm air ahead of it to rise rapidly. Trewartha (1968, p.104) suggests that under normal conditions the slope of a cold front surface is very steep because the advancing cold air at the ground surface is held back by friction, which gives it a tendency to be more advanced just above the surface. Because of this, the warm air rises rapidly and precipitation usually occurs along the leading edge of the front. The amount of precipitation depends on the characteristics of the warm air that is being uplifted and the rate of uplift. Trewartha (1968, p.205) suggests that in general, the steep slope of the cold front results in vigorous uplift and that pelting rain for short periods can occur (line-squalls). In most situations involving mP air, the showers resulting from cold frontal uplift do not cause more than very local flooding. If prior soil moisture storage has been at high levels, however, and if greater than normal frequencies and/or intensities are experienced because of cold air aloft, etc., more widespread flooding may be experienced. If mT air masses are present in the warm sector, cold frontal uplift may result in much greater precipitation because this air, although infrequently present, is usually much warmer and moister than mP air which has dropped a part of its moisture supply in crossing the mountains. Examples of floods from this climatic activity are presented in the June 1964 flood in Montana (Boner and Stermitz, 1967) and southern Alberta and the June 1953 (southern foothills) and June 1972 Smoky River

Basin floods (Warner and Thompson, 1974). These examples will be discussed in the sections dealing with convergent air masses and orographic precipitation, respectively.

ii) Warm Fronts (II.a.2):

Warm fronts occur where a warm air mass often associated with a Pacific cyclonic storm overrides cold surface air. The inclination of the frontal surface is relatively gentle because frictional drag tends to flatten out the wedge of retreating cold air. As the warm air slowly moves up the shallow frontal incline over the cold air, adiabatic cooling results and this may lead to cloud condensation and precipitation. The character of the warm air mass and rate of uplift again determine the amount of precipitation which can occur. If the warm air is convectionally unstable, ascent over the cold wedge may cause showers ahead of the surface front (Trewartha, 1968, p.203). Trewartha states that warm frontal precipitation tends to be fairly steady, long in duration and widespread.

Warm frontal uplift in combination with orographic uplift causes significant rainfall along the coast of British Columbia. In the Prairies, however, the mP air masses have lost much of their moisture over the Cordillera, and there is little cloud development on warm fronts at low levels. Laycock (personal communication, March 1981) suggests that since there is little heat of condensation addition with lower level uplift, there is not much convectional activity (as in cold fronts), and therefore warm front rains and snows in the Prairies from mP air masses are light or absent. Substantial rainfalls on the Prairies do occur, however, from warm frontal uplift of mT air masses.

iii) Orographic Precipitation (II.a.3):

Orographic precipitation occurs where an upland obstruction forces an air mass to rise and cool. Water vapor is mainly confined to the lower layers of the atmosphere and rapidly decreases upwards. When the water vapor is forced upwards by the mountains, condensation and heavy orographic rain can occur. Warner (1973, p.87) suggests

that if the mountains are aligned at right angles to the direction of the wind, heavier orographic precipitation may result. Trewartha (1968, p.151) states that the obstruction need not be exceptionally high to cause orographic uplift. After an unstable air mass has been lifted to the condensation level, the added heat of condensation makes it unstable and buoyant causing continued uplift and convective rainfall. This factor will be illustrated in the following example.

In June 1964, extensive flooding associated with orographic and cold frontal uplift of a mT air mass occurred in Montana and southwestern Alberta. Warner (1973, pp.79-88) has examined in detail the meteorological conditions which caused the flood. In the beginning of June, moist warm air from the Gulf of Mexico moved north and northwest over the western plains and central Rocky Mountains. By June 7, when rains associated with the flood started, the moisture laden air mass entered the northeast portion of a low pressure area which was centered over Idaho. As the mT air mass hit the eastern slopes, intense orographic uplift and precipitation occurred. Along this portion of the eastern slopes the rainfall was very heavy. On the morning of June 8 a cold front from the north moved south and forced the warm mT air mass to rise. The heaviest precipitation lasted approximately four hours. Along portions of Montana's eastern slopes up to 400 mm of precipitation fell in a 40 hour period.

Warner (1973, p.88) suggests that it would be difficult to design a combination of factors more favorable for a heavy rainfall than occurred in the 1964 storm. The maximum vertical motion centers were located above the steepest eastern slopes of the Montana and Alberta Rockies; the flow of moist air from the Gulf of Mexico was unusually direct, broad, and undisturbed until it arrived in the rain area; and the wedge of cold air from the north was perfectly timed to provide several hours more of heavy rain.

Most of the severe flood damage occurred in Montana and is described in detail by Boner and Stermitz in the 1967 U.S.G.S Water Supply Paper, 1840-B. In Southern Alberta, extensive flooding also occurred. Waterton was badly flooded when over 400 mm of rain fell on June 7 and 8 in the adjoining mountains causing many of the local

streams to flood and the lake level to rise 1.2 metres.

Along the southern coast of British Columbia, including Vancouver Island, winter flooding is often experienced when warm, moist mP air is orographically uplifted and large amounts of rain fall on the mountains and low-lying areas during relatively short periods. Recently, four winter floods of this nature have occurred. In December 1979, over 100 mm of rain was recorded during a 24 hour period, flooding many low lying areas of the Fraser River Delta and Vancouver Island. Total precipitation for the week of December 12 - 18 was 170.9 mm at the Vancouver Airport and 700 mm in the Jordan River basin on the west coast of Vancouver Island.

During the writing of this thesis, a severe flood of this type occurred on December 26, 1980. Substantially more precipitation would have fallen on the local mountains during this period, and well over 125 mm of rain was recorded in many lower mainland communities. Times-Colonist (Dec. 2, 1980, p.1) reports that 83.8 mm of rain fell in Victoria over a three day period with 45.2 mm of rain falling on December 26, 1980. Record high temperatures on December 25, 26 and 27 (15.5 °C, 14.5°C and 13.3°C respectively) also caused extensive melting of the snowpack on the coastal mountains. The combination of these factors produced the worst flooding in southwestern British Columbia since the spring floods of 1948. B.C. Environment Minister Stephen Rogers authorized $13 million for disaster relief, but the final cost from this flood may not be determined for several years. The recurrence frequency of this event would not be very high, but to the author's knowledge, has not been determined. In December 1981, substantial flooding from rain occurred in this area, although damage was somewhat less.

Thompson (1976) has analysed existing records for the 1897, 1902 and 1915 rain storms which caused severe flooding in Alberta. In all three cases, a warm moist air mass encountered a low system which formed in Montana and then moved northward into Alberta. The rain fell from the northern edge of the surface low as it moved northward. Thompson (1976, p.10) states that in each storm the precipitation was intensified by an upslope flow of the moist air over

the foothills.

iv) Convectional Precipitation (II.a.4):

Convectional precipitation is caused by the adiabatic cooling of buoyant air currents which rise vertically. The trigger mechanism which starts the uplift can be caused by heating of the ground surface, by uplift over a terrain obstacle, or by uplift along fronts where less dense air is forced up over cold dense air and the added heat of condensation results in uplift. The rainfall associated with convective cells can be very intense and is often referred to as thundershowers. Laycock (1972, p.14) suggests that the greater portion of the plains precipitation falls from Pacific air masses which are often associated with cold frontal and/or convectional uplift.

The rainfall experienced from a thunderstorm is associated with the size and stage of development of each cell (Trewartha, 1968, p.227). Rain is heaviest under the core of the cell and decreases towards the margins. In slow moving cells heavy point precipitation may be experienced which can result in significant runoff depending on prior soil moisture conditions. The rainfall can be very intense and localized as the following examples will illustrate.

On June 26, 1975, the Regina area was hit by a major thunderstorm which dropped up to 150 mm of rain in a period of four hours. The storm backed up storm sewers and caused extensive flooding in residential areas. A week earlier a small thunderstorm which dumped 25 mm of rain in 20 minutes had caused more than $250,000 damage.

Fluto and Lemieux (1975, p.1) describe the meteorological events which led up to the May 20, 1974 thunderstorm in the Winnipeg area;

> "Prior to the Victoria Day storm, upper level charts showed a deep trough over the southwest United States and a strong southerly flow across the northern plains. On May 19, a disturbance moved through this trough and tracked northeastward, resulting in a general rainfall of one to two inches over southern Manitoba. In the wake of this system a more intense wave, involving the Polar Front, developed over northern Colorado. The strong southerly flow ahead of the rather slow moving system brought increasingly moister air over the Dakotas. This air mass was potentially unstable and lifting associated with the Polar Wave was sufficient to release this instability on the evening of May 20th. Heavy thunderstorms

moved across southern Manitoba and substantial rainfall occurred in Winnipeg and area."

Because of the rainfall prior to the May 20th thunderstorm the ground was saturated and runoff on the 20th was rapid. Storm sewer systems backed up, and water from 200 to 600 mm in depth caused extensive flooding in residential areas.

Thunderstorms in Western Canada occur most commonly in the southern parts of the three prairie provinces and certain interior locations of British Columbia but are not confined exclusively to these locations. Weber (1980, personal communication) states that rainfall floods from intense thunderstorms are not uncommon in small watersheds (less than 260 square kilometres in area) in Manitoba.

v) Convergent Air Masses (II.a.5):

Trewartha (1968, p.152) suggests that whenever surface air stream convergence occurs, lifting of the air masses results, and atmospheric instability increases. In Western Canada the air masses which are present often differ in temperature and density. When two air masses with different physical features converge, extensive atmospheric disturbances can result when the warmer less dense air mass rises over top of the colder, denser air mass. This meeting or convergence of contrasting air masses is usually cyclonic in origin and can commonly result in the formation of precipitation. Trewartha (1968, p.152) states that a slight amount of uplift along a convergent sector may provide the trigger effect necessary to start vigorous convective overturning, especially in the warmer months, and heavy rains can result. This type of storm is often the cause of heavy precipitation over the foothill region of Alberta.

In June 1972, the uplift of mT air in the warm sector of an intense low (a strongly convergent situation) caused extreme rainfall and extensive flooding in the Southern Peace (Smoky River) basin in Alberta. Warner and Thompson (1974, pp.6-11) have documented in detail the meteorological events which occurred during and prior to the heavy rains. In review, on June 11 a cold low moved off the Pacific coast and inland over Washington. East of the low, a ridge

with associated warm air extended northward over Saskatchewan and northern Alberta. At the same time, an elongated trough existed at the surface, east of the Rockies, with a low beginning to form near Calgary. Fairly warm, nearly saturated air covered northeastern British Columbia and much of Alberta. The cyclonic circulation forming around the developing low had just begun to transport the warm, moist air westward across north central Alberta forcing it to rise over the foothills of the South Peace River basin. Southeast of the low center (at Calgary), a cold front marked the leading edge of a surge of cooler, dry air advancing eastward over southern Alberta.

At 1800 M.D.T., June 11, the low center had moved from Washington into southeastern British Columbia. The surface low had moved from Calgary northward to just south of Edmonton, and the easterly wind based upslope of warm, moist air over the foothills was well established causing heavy rains to occur over the South Peace River basin. The warm air later spiralled around the northwest side of the low prolonging the rainfall.

Warner and Thompson (1974, p.12) state that the convergence associated with the low contributed much of the vertical motion and precipitation, but that the lifting of the warm moist air was also assisted by the upslope conditions of the foothills. These two elements created a tremendous uplift which resulted in more than 150 mm of rain falling over a thirty-six hour period.

The runoff from the rain caused extensive flooding and damage at Grand Prairie, Alberta and in surrounding areas. The flood waters of the Peace and Smoky Rivers combined simultaneously at the town of Peace River with a flow of 15,575 m^3/s. Warner and Thompson (1974, p.1) suggest that without the influence of the Bennett Dam on the Peace River, the combined discharge at Peace River townsite would have been 22,650 m^3/s, which would have caused a stage about 1.8 metres higher than actually occurred. The townsite experienced some flood damages, but dykes helped to significantly reduce the effects of the flood.

vi) Cold Air Aloft (II.a.6):

Rainfall from cold air aloft is basically an intensification of convective uplift and rainfall. As was mentioned in the previous section, convectional currents lift warm humid air vertically and as the air cools, condenses and stabilizes, a convective cell develops. However, if cold air is sitting above the rising air mass, the normal lapse rate is exceeded and the comparatively warm air mass rises more rapidly to greater heights and exceptional amounts of convection can occur. In August 1954, a cold airstream which originated from an area north of Siberia passed over the Edmonton area. Unstable convectional uplift from the lower atmosphere into the cold jet stream resulted in heavy rains in the foothills of the North Saskatchewan River basin. These rains were responsible for washing out some of the construction operation on the Groat Bridge in Edmonton (Laycock, personal communication, January 1981).

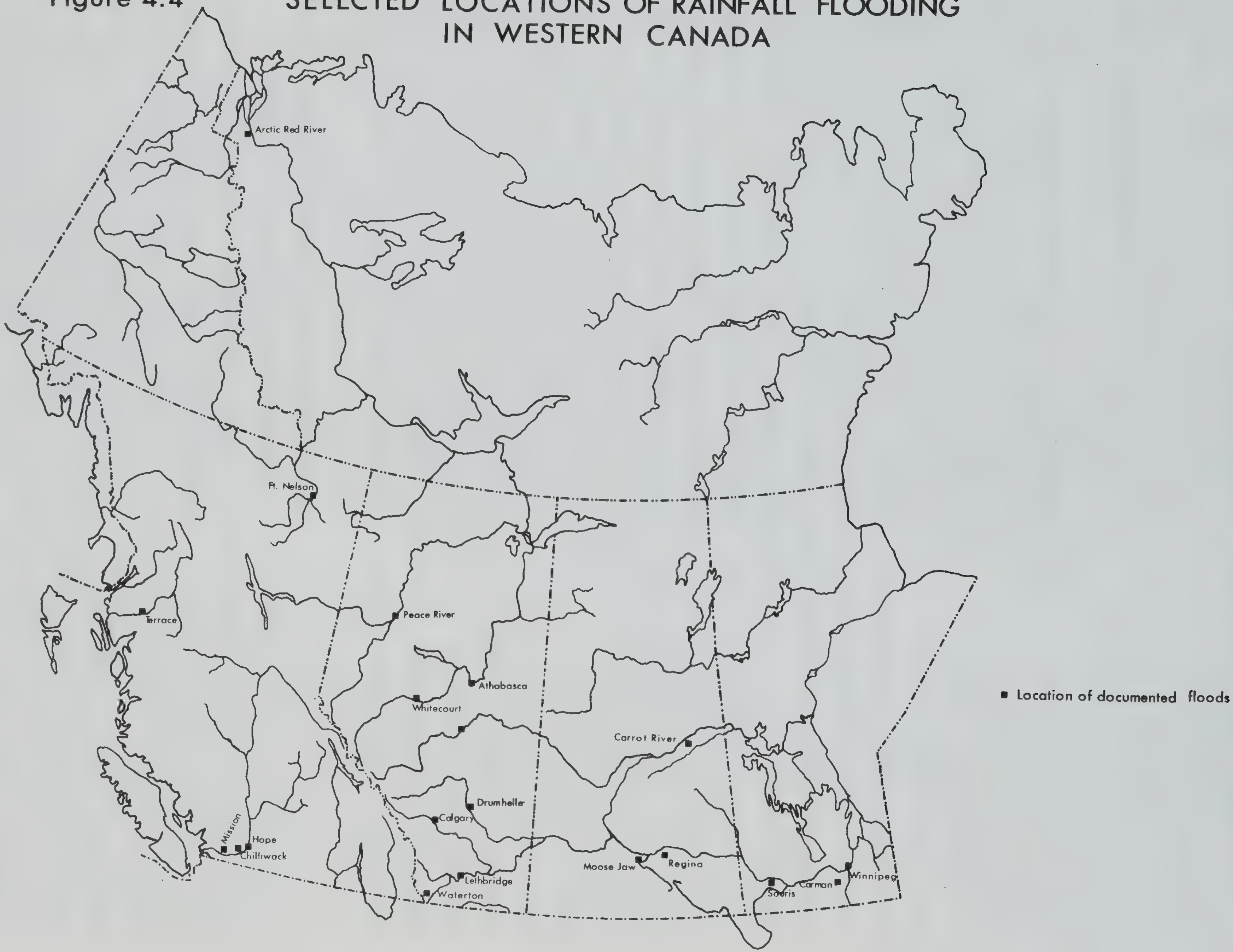
In July 1970, severe flooding occurred in the Arctic Red and Mountain River basins in the Northwest Territories. MacKay, Forgarasi and Spitzer (1973) suggest that vertical instability in combination with cold air aloft were the main causes of the intense precipitation which fell on the eastern slopes of the Mackenzie Mountains. Henoch (1960) mentions that rain storms from orographic and convectional uplift are not uncommon in this region. The presence of cold air aloft, however, significantly intensified the convectional uplift. MacKay, Forgarasi and Spitzer (1973, p.216) report that the natural damages and changes to the flood plain were significant, but provide no indication (if any) of the flood effects to the towns of Martin House or Arctic Red River. They also state that;

> "Based on tree-ring data, the intensity of the storm and the flooding that followed were such that the occurrence of a similar event in any given year has a probability of less than one per cent."(MacKay,Forgarasi and Spitzer, 1973, p.216)

It is interesting to note that it was possible to determine the return period for this flood event solely on the basis of tree-ring data and with no other substantiating data.

The locations of many of the previous examples of rainfall flooding are presented in Figure 4.4. Other documented cases of

Figure 4.4 SELECTED LOCATIONS OF RAINFALL FLOODING IN WESTERN CANADA



this form of flooding located by the author are also indicated in Figure 4.4.

4.3.3 Snowmelt (III):

4.3.3.1 Snowmelt by Stages - A Contributing Factor (III.a):

In many years a gradual rise of the freezing level in the free atmosphere results in a moderately slow runoff from lower to higher levels. While the magnitude of the yield depends upon the size of the snowpack and the rates of temperature rise above the freezing level, flooding from this causal factor alone rarely occurs. Many authors including Chow (1964) have explained the causes of snowmelt. If other flood causal factors, such as rainfall, were to occur in combination with the yield from the slow snowmelt, significant flooding could occur. For example, if snowmelt in the upper Fraser River basin was proceeding at a steady normal rate, the level of the Fraser River would probably be below bank level and no significant flooding would occur. Heavy rainfall in the southern portion of the watershed combined with unseasonal high temperatures, however, could add enough runoff to raise the river above bankfull capacity and flooding would occur. Therefore, while not a major flood causing factor, normal snowmelt by levels (when in combination with other flood causal factors) can contribute significantly to flooding.

4.3.3.2 Rapid Snowmelt Flooding (III.b):

When the snowmelt occurs rapidly, it ceases to be a contributing factor and can often become the principal flood causal factor. For example, during the winter of 1947-48, a large snowpack accumulated in the Fraser River basin. The spring of 1948 was unusually late, and the freezing level rapidly lifted. The result was a record spring flood in the Fraser River basin with damages in excess of $17 million (1948 dollars) (Fraser River Board, 1958, p.c-11).

Snowmelt flooding can also occur when a heavy late snowfall suddenly melts. In late April 1979, spring flooding occurred in southern Saskatchewan and Manitoba when a sudden thaw followed an

early spring snowfall and an unusually long period of below-freezing temperatures (Daily Colonist, 1979, p.6). In Saskatchewan, the Weyburn and Estevan areas were badly flooded with rain also contributing to the flooding. In Manitoba, runoff from snowmelt and rain produced the most severe floods experienced in the Red River basin since 1950. The Red River was only a few centimetres lower than the 1950 levels. Rannie (1980, p.212) reports that in Manitoba damages from this flood event could be as high as $30 million. Environment Canada (1981, p.vii) states that approximately 1550 square kilometres were flooded in Manitoba.

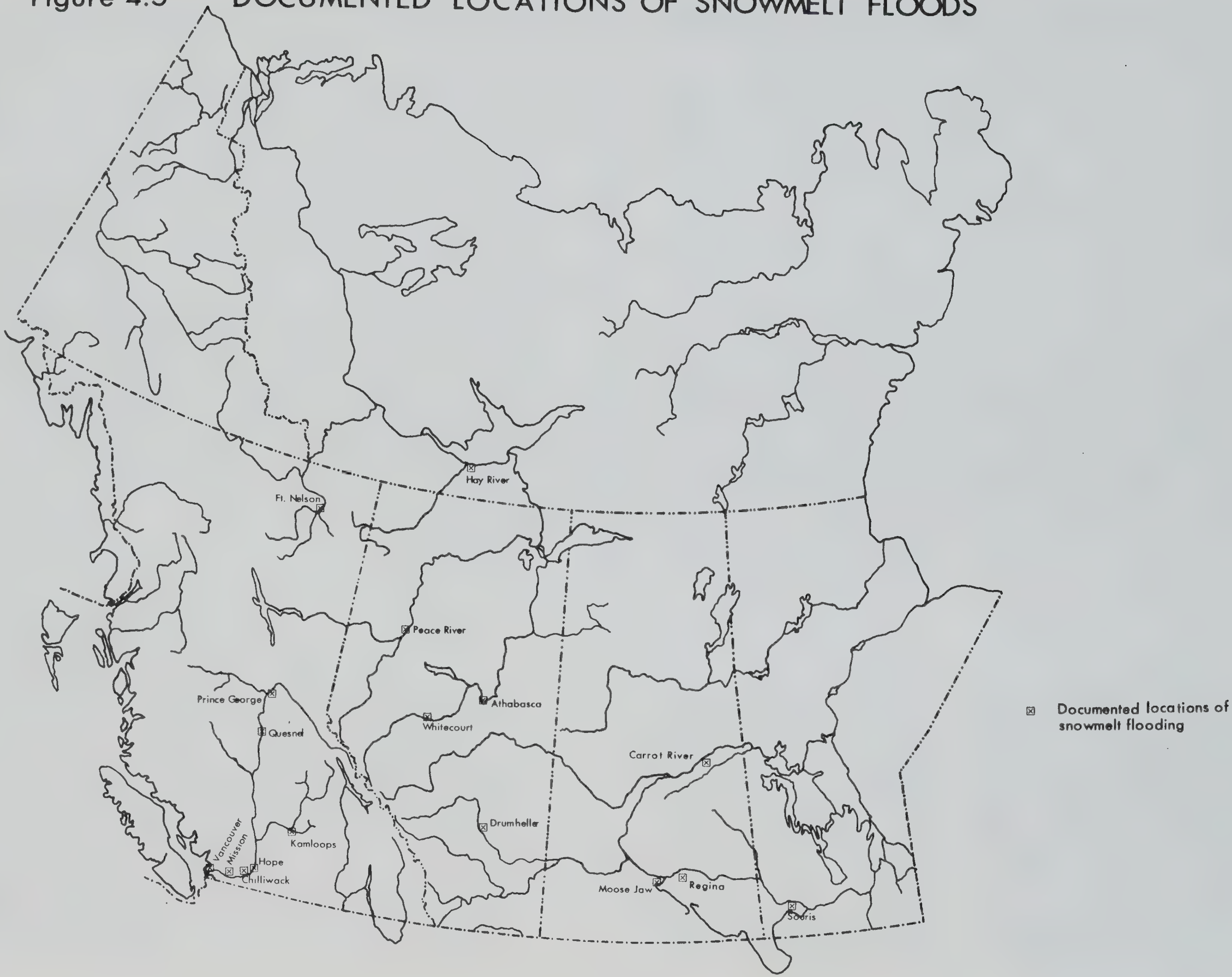
Snowmelt runoff from a sudden warm spell during winter can also contribute to flooding. In December 1980, this was one of the main causal factors in the extensive floods which occurred in south-western British Columbia. Three days with record warm temperatures forced the freezing level to rise above the elevations of the coastal mountains. Very rapid snowmelt of a large snowpack in combination with rainfall and saturated soil conditions caused major flooding.

It will be shown later in this chapter how snowmelt contributes significantly to other flood events. While a major contributing factor to runoff, snowmelt is usually one of several factors which can combine to cause a flood.

Flooding from snowmelt runoff can occur in many of the river basins in Western Canada (Figure 4.5). There are, however, a number of regions where snowmelt is either a secondary factor to flooding or is not a factor at all. As Figure 4.5 indicates, snowmelt is not a documented factor in any of the urban communities in the N.W.T. Mr. J.N. Jasper and Mr. R.W. Hornal of the Department of Indian and Northern Affairs in the N.W.T. provided the author with a comprehensive list of the flood problems experienced by the urban communities in the N.W.T. While there were detailed descriptions of ice jam and rainfall floods, no reference was made to snowmelt flooding. It is assumed, however, that this can be a causative factor in this region.

Generally, snowmelt is only a contributing factor during floods experienced on Vancouver Island. Foster (1979, p.65) states that

Figure 4.5 DOCUMENTED LOCATIONS OF SNOWMELT FLOODS



floods on Vancouver Island rivers occur during the winter months from heavy rainfall rather than from spring snowmelt (as is normal for other rivers in Western Canada). However, abnormal snowmelt on Vancouver Island can be considered a contributing factor to flooding because in some years heavy snowpacks have been recorded on the Vancouver Island Mountain Range. In the spring of 1983 a very large snowpack in this region caused government officials in the Ministry of Environment a great deal of concern.

Fenco (1974, pp.24-33, 72-75) reports that snowmelt flooding occurs in the communities of Ross River and Mayo, Yukon Territory. Since a stream gauging station was installed on the Pelly River at the town of Ross River in 1954, two major snowmelt floods have occurred. In 1964 snowmelt runoff accompanied by rainfall flooded the town, and in 1972 flooding occurred from a combination of high May temperatures, the melting of a large snowpack and heavy rains.

4.3.4 Prior Ground Moisture Conditions (IV):

4.3.4.1 Antecedent Conditions (IV.1.a&b):

Aside from snowmelt and rainfall, antecedent soil moisture conditions are generally the most referred to of the flood causal factors in the reports on flooding in Canada and the United States. For the purposes of this flood causal classification, antecedent conditions will be referred to as the soil moisture condition prior to a flood event. If the ground is saturated or frozen prior to snowmelt and/or an intense rain event, runoff will often be very rapid and can contribute to severe flooding. In general, antecedent soil moisture is a potential flood causal factor in every region of Western Canada except for high alpine areas of the Cordillera and northern reaches of the Northwest Territories. For example, prior to the heavy rains which caused the June 1964 floods in the Oldman and Milk River basins, snowmelt created saturated soil conditions. Warner (1973, p.6) reports;

> "Large scale melting of the snowpack began towards the latter part of May and continued into June at a sustained high rate. The resulting high soil moisture content and high streamflow were conducive to the rapid

> response of most streams in the flood area when the storm of June 7 and 8 struck."

Boner and Stermitz (1965, p.B5) also report that the soil moisture in the Milk River basin and the Montana foothills was near field capacity because of cool weather and above average precipitation in April and May.

A similar situation occurred in the Carrot River basin in central Saskatchewan in 1957. Collier (1965, p.20) reports that natural storage was relatively high in the basin prior to the 1957 spring flood, as a result of the preceding 30 month period of abnormally high precipitation. When heavy rain fell in late April the soil was unable to absorb the runoff and serious flooding resulted (other causal factors were also responsible for this flood and will be discussed in later sections).

Antecedent soil moisture storage can also become a major flood causal factor when ice forms on the soil surface (causal factor IV.b). For example, if a very wet fall is suddenly followed by a long cold snowy winter, a layer of ice could form on and within the soil surface freezing the ground solid. If during the spring snowmelt heavy rain fell on the still frozen ground, the impervious surface would contribute to accelerated runoff and could create severe flood conditions. Flooding from this situation occurred in May 1965 in the Upper Mississippi River basin and caused $160 million in damages (Anderson and Burmeister, 1970, p.A1). Severe flooding of this type also occurred in the Cypress Hills region of Alberta and Saskatchewan in 1952. During the fall of 1951, heavy precipitation prior to the onset of freezing temperatures left the ground soils saturated. A sudden freeze turned the soils into "concrete" ice. Late heavy snows fell during the winter, and in the spring when warmer temperatures caused the snow to melt, there was little infiltration into the surface soils. As a result, the runoff was rapid and caused significant flooding in the area (Laycock, personal communication, 1982).

4.3.5 Oceanic and Coastal Factors (V):

4.3.5.1 Tsunami Floods (V.a.1&2):

The presence of an active seismic zone along the west coast of Canada and the proximity of this area to other seismically active regions in the Pacific basin exposes most of the low-lying coastal regions of British Columbia to flooding from tsunami inundation. Foster and Wuorinen (1976, p.113) describe tsunamis as "trains of seismically triggered sea waves, most frequently generated by submarine dip-slip faulting, which are capable of causing extensive damage in low-lying coastal areas." Foster further reports that between 1900 and 1970, 138 tsunamis, of which 43 were destructive, have been recorded in the Pacific basin.

Tsunamis are capable of travelling great distances at speeds in excess of 960 kilometres per hour. The dangers from tsunamis, therefore, are not confined only to the areas of origin. Of the ten tsunami wave trains measured at the Tofino tide gauge, none have been generated locally. For example, the 1964 Alaska earthquake generated a series of tsunamis which caused extensive flooding and destruction on the west coast of British Columbia, particularly along the Pacific coast of Vancouver Island. The greatest destruction occurred at Port Alberni on Vancouver Island when a series of tsunamis funnelled down the long, narrow Alberni Inlet and piled up on the townsite. Flooding was extensive and the resulting damage has been estimated at $10 million (1964).

The distribution of endangered areas from future tsunamis is difficult to predict. In Table 4.4, however, Foster and Wuorinen (1976, p.116), with assistance from S.O. Wigen of the Canadian Hydrographic Services in Victoria, have attempted to rank the coastal communities on Vancouver Island according to the tsunami risk; low, medium or high. This classification is based on the exposure, site topography, and altitude of each settlement.

Like many other causal factors, tsunamis could cause severe flooding if they occurred in combination with other events. For example, if a tsunamis were to occur during spring runoff when the

TABLE 4.4

TSUNAMI-ENDANGERED VANCOUVER ISLAND SETTLEMENTS

Settlement	Risk*
Alert Bay	M
Bamfield	M
Beaver Cove	M
Coal Harbour	L
Fort Rupert	M
Franklin River	H
Gold River	H
Holberg	L
Kyuquot	M
Long Beach	M
Mahatta River	M
Port Alberni	H
Port Albion	H
Port Alice	H
Port Hardy	M
Port McNeill	M
Port Renfrew	M
Quatsino	L
Sointula	M
Tahsis	H
Telegraph Cove	M
Tofino	M
Ucluelet	H
Winter Harbour	H
Zeballos	H

*High (H), Medium (M), Low (L).

Source: Foster, Harold D. and V. Wuorinen. 1976. "British Columbia's Tsunami Warning System: An Evaluation." Syesis. 9. University of Victoria. pp.113-122.

river levels were high, a bore effect caused by the tsunami moving up a major river could cause localized flooding. It should be noted, however, that the probability of this occurring is very low. The return period for a major tsunami could be very long.

Following the tsunami damage caused by the 1964 Alaska earthquake, Canada rejoined the Pacific-wide seismic sea wave warning network which is controlled by the International Tsunami Information Center in Honolulu, Hawaii. This complex warning system alerts member countries located in the Pacific basin of any seismic activity which could potentially result in the formation of a tsunami train (usually an earthquake registering 6.5 or greater on the Richter Scale). Once a tsunami has been confirmed, the arrival time at various Pacific coastal locations is estimated from travel time charts (considered accurate within 2.3 percent) prepared for each tide station in the system (Foster and Wuorinen, 1976, p.118). Based on the information received from Hawaii a warning system has been established by the government of British Columbia to alert coastal communities as to the estimated time of arrival. This warning system has been described elsewhere (Erb, 1965; Foster and Wuorinen, 1976). Aside from warning systems other flood damage reduction alternatives which could be considered by the planner include public education programs, evacuation plans, identification of sites subject to inundation, restricting development at high risk locations, moving hazardous storage facilities such as oil tanks away from water and, where feasible, the construction of break walls such as those located at Hilo, Hawaii, and Crescent City, California. The previously described research conducted by Mr. Wigen of the Canadian Hydrographic Services could provide much of the foundation for planning.

4.3.5.2 High Tides (V.b):

High tides are not an important flood causal factor, but in several locations in Western Canada they can be considered to be contributing factors. For example, Hornal and Jasper (personal communication, August 1980) suggest that low-lying parts of Tuktoyoktuk, which is located on a peninsula extending eastward into the Beaufort

Sea from the MacKenzie Delta (Figure 1.1), can experience flooding under the appropriate conditions. High monthly tides in combination with wave action and the wind set can apparently result in limited flooding.

This can also be a local problem in certain coastal areas of the Fraser River Delta. When extremely high tides occur in combination with a high water table, residential basements have flooded.

4.3.5.3 Wave Surges From Slide Activity (V.c):

Destructive waves can be generated in coastal bays when large sections of mountains or glaciers slide into the water. The displacement created by the solid mass can create an extremely large wave (see Dam Failure section). The best local example of one of these slide generated waves occurred in Lituya Bay which is located north of Sitka, Alaska in the "Alaskan Panhandle." Lituya Glacier is located at the north end of the long T-shaped fiord. On July 9, 1958, an earthquake along the Fairweather fault triggered a landslide of approximately 90 million tons of rock and ice on Lituya Glacier. Tufty (1969, p.118) states that the mass slid approximately 0.8 kilometres into Lituya Bay which sent an immense wave across the bay at over 160 kilometres per hour. The wave apparently surged over 520 metres up the mountain slope on the opposite shore, removing all vegetation and killing two people (sparsely populated area). Tufty (1969, p.118) includes an eyewitness account which, if valid, would illustrate the size of this wave;

> "Two eyewitnesses, Mr. and Mrs. W.A. Swanson, tell that in only a few minutes their forty foot travelling boat, the Badger, was lifted up by the huge wave and thrust ahead of it stern first just below the crest. Hurled over a point of land called La Chaussee Spit at the bay's entrance, Mr. Swanson looked down a distance of eighty feet onto the tops of trees growing on land below, just before the wave crest broke and dropped the boat safely in the ocean outside the bay."

Whether this account is exaggerated or not, the other evidence for this event is spectacular.

The potential exists for a flood wave of this type to occur in many areas along the B.C. coastline. However, the probability and frequency of occurrence would be very low at any single location

and this factor should not be seriously considered in most areas.

4.3.5.4 Storm Surge Waves (V.d):

Storm surge waves are not a major flood causal factor in Western Canada, but have caused substantial flooding in other areas, notably in the United States and in Holland, Denmark and West Germany. For example, recent storms on the North Sea in November 1981 caused significant storm surge floods in the latter two countries. There are, however, reports of storm surge floods along the coastline of Alaska and Canada on the Beaufort Sea. Reimnitz and Maurer (1979, p.329) report that in 1970 a major storm surge caused by gale-force winds inundated low-lying tundra areas as far as 5000 metres inland and left a driftwood line as much as 3.4 metres above normal sea level along the Beaufort Sea coast of Alaska. Henry (1975) has recorded two surges about 1 metre high along the Canadian portion of the Beaufort Sea during the winter of 1973-74. Reimnitz and Maurer (1979, p.341) state that three surges, 94, 140 and 69 cm, were recorded at Oliktok, Alaska during January and February 1973.

The potential for storm surge activity along the Pacific coast of Western Canada exists, but the author feels that this would be a very localized flood situation were it to occur. It suffices at this point to simply make reference to this type of flood hazard.

4.3.6 Lake Flooding (VI):

4.3.6.1 Landslide Induced Wave Surges (VI.a):

In the Cordillera region of Western Canada, many communities are located beside lakes where there is a potential for landslide generated wave surges to occur. Although no examples of this form of dynamic flooding were located, the documented case studies presented for the causal factors V.c -- wave surges from coastal landslide activity and VIII.c.3 -- dam overtopping, adequately illustrate the possibilities. Kootenay Lake, in southeastern British Columbia, provides an excellent hypothetical example of the potential for lake-shore flooding by landslide-generated waves in the Cordillera.

The lake is approximately 60 metres deep and if a substantial landslide dropped into the lake, many of the urban communities situated around Kootenay Lake (including the larger centers of Nelson and Kaslo) could experience significant flooding from a wave surge. While the exact nature of the stratigraphy in this region is unknown to the author, and therefore the probability of this flood type of flooding actually occurring cannot be established, this example serves to illustrate the potential nature of the hazard.

For an individual location in Western Canada the frequency for flooding of this type would be extremely low and near impossible to calculate. Landslides into lakes would be more common in reservoirs because of slope undercutting by wave action (causal factor V.c & VI.a). For a description of possible flood damage reduction alternatives, refer to Section 4.3.1.3.

4.3.6.2 Lake Level Fluctuations (VI.b):

Lake level fluctuations have caused significant shoreline flooding in many lakes in Western Canada. For example, in 1972 the Alberta Department of Environment released a study which identified many of the problems associated with 70 lakes in the province. Their findings indicated that 63 percent of the lakes experienced shoreline flooding and a further 9 percent had a problem with lake level fluctuations (Alberta, Department of Environment, 1972, p.5).

Based on the literature reviewed, the majority of documented lake shore floods have resulted from runoff during intense rainstorms (once again, the contributions of other causal factors, if present, have not been acknowledged). Weber (personal communication, 1980) suggests that during this period the flood problems can be compounded by wind set and wave uprush. In support of this statement, Warner (1972, p.28), when studying the June 1964 precipitation floods in the Oldman and Milk River basins in southern Alberta, states;

> "The Waterton Park townsite, which is bordered by Waterton Lake, was the scene of very severe flooding. The lake rose four feet in a three hour period early on June 8. A brief 70-mph north wind created waves on the lake that smashed boats at the Waterton Lake pier."

Lesser Slave Lake in Alberta also suffers from extensive and

frequent lake shore flooding. Nemanishen and Meeres (1980, p.57) report that during the period 1914 to 1978 significant floods were recorded around the lake in 1914, 1920, 1935, 1965, 1971, 1974, 1975 and 1977. Essentially, rain precipitation runoff was identified in all cases as the principal flood causal factor, and in most cases as the only causal factor. For the flood of 1935, Nemanishen and Meeres (1980, p.83) have identified excessive antecedent soil moisture conditions and prior snowmelt runoff as contributing factors, and for the 1971 flood similar soil conditions were also acknowledged.

Alberta is not, however, the only area in Western Canada where lake flooding is a problem. Obtaining information for the other regions of Western Canada was difficult, but several examples were located. Fenco (1974, p.52) reports that lake level fluctuations on Teslin and Marsh Lakes in the Yukon Territory have caused flooding of private property in past years (years not identified). The 100 year return period for water elevation has been determined for Teslin Lake using measurement data from the Water Survey of Canada for the period 1945 to 1973. These data have been used to identify a flood zone around the lake shore, and 16 properties were located within this zone.

Weber (personal communication, 1980) suggests that shoreline flooding of lakes sometimes occurs in Manitoba due to excessive lake inflows. Weber failed to identify which lakes were involved, but it is assumed that Lakes Winnipeg and Manitoba experience this problem.

In British Columbia, Fumalle (1973) estimated damage around Okanagan Lake following a 1972 flood. Apparently, in early July 1972, the elevation of Okanagan Lake peaked at almost 23 cm above its normal maximum. The damages to local residences around the lake were not found to be extensive. High water levels have been experienced on Okanagan Lake seven times (1921, 1928, 1942, 1946, 1948, 1951 and 1972) during the period of record 1920 to 1974 at Penticton (Environment Canada, 1980, p.96).

In Alberta the water balances of Gull Lake, Cooking Lake and others have been studied (Laycock, 1973). The very wet years of

the 1900 to 1907 period resulted in these lakes having overflow. In subsequent years, levels have declined irregularly by two to four metres and cottagers have located buildings, roads, etc. below the old overflow levels. In some moderately wet series of years (e.g. 1953-56, 1971-74), some have suffered flood damage. Hay meadows and other agricultural lands suffer damage in wetter years (e.g. "Burnt" Lake near Sylvan Lake, Hay Lake).

4.3.7 Engineered River Channel Obstructions (VII):

4.3.7.1 Bridges and Debris Floods (VII.a.2&3):

Earlier in this chapter it was explained how flooding could occur if a bridge obstructed the flow of ice during spring break-up. It is also possible for bridges to block floating debris on the river surface when the river is in a high stage. Many of the older bridges in Western Canada were constructed relatively low to the river and when high discharges occur it is not uncommon for logs, driftwood and other material to bind up against the bridge and form a dam. When this occurs, the river has restricted flow under most of the bridge, and water is forced out and around the structure, often flooding the local urban or rural areas. For example, the Montreal Engineering Company (1968, sheet 9) suggests that both the Hillhurst and Center Street Bridges in Calgary would have this problem. The Hillhurst Bridge, which was constructed in 1920, has arched sections that are supported by massive piers. The bridge has very little clearance, and if the Bow River were to reach a discharge in excess of 1415 m^3/s, driftwood would jam against the bridge and water would divert into the Hillhurst district to the north and into downtown Calgary south of the river. When the river discharge reaches 1700 m^3/s a similar flood situation would develop around the Center Street Bridge and water would be diverted into the downtown area of Calgary.

During the June 1971 flood at Fort Nelson, British Columbia, the Bailey Bridge which crossed the Fort Nelson River caused a massive debris jam upstream from the bridge. Water was diverted around the

bridge washing out the road approaches and flooding the adjacent land. The pressure exerted by the debris jam later removed the whole bridge.

It is essentially impossible to predict when and where this type of flooding will occur in Western Canada. Basically, it could happen at any location where the bridge design does not allow the free passage of drift material during a high stage. There also has to be a source of debris present in the vicinity of the river channel to provide the material necessary to form a jam. In most rivers in Western Canada this latter requirement is available, because even in the drier regions trees do grow alongside rivers.

4.3.7.2 Landfill and Dykes (VII.b):

a) Landfill - Reduced Channel Capacity (VII.b.1):

As was previously discussed in several other sections of this chapter, any obstruction which reduces the channel capacity of a river will contribute to flooding during high yield periods. Landfill can be particularly hazardous in this respect, because by constricting the river channel, the stage of the river can be increased (Montreal Engineering Co., 1968, Sheet 1). This can often lead to the flooding of areas which would possibly have remained dry if the river channel had been left alone.

The Montreal Engineering Company (1968) was able to identify many sections of the Bow River in Calgary where landfilling along the shore had significantly constricted the river channel. During a period of high discharge the river could possibly be forced over the river banks because the channel capacity would be exceeded.

b) Dyke Constriction of Flow (VII.b.3):

When attempting to control flooding, man can often inadvertently contribute to it. For example, by lining a river with dykes, man removes much of the on-stream storage capacity for that section of the river which is dyked. During high discharge periods the dykes constrict the flow which would ordinarily spill over the river banks

and onto the flood plain. Often the river level between the dykes rises well above the level of the flood plain. When the dykes end, the flood waters flow outward from a river channel which does not have the capacity to contain this volume of water, and flooding can occur. On the Fraser River Delta near Vancouver, this problem does not exist because dykes line the river channel right up to the point where the Fraser empties into the Strait of Georgia. However, in the Manitoba portion of the Red River basin, the only major reservoir available is Lake Winnipeg. Upstream from this reservoir, however, dyking has only been designed to protect the local communities and after the water passes between the dykes it spills out onto the rural countryside. Mudry, Reynolds and Rosenberg (1981, p.23) report;

> "Dykes to protect agricultural lands are not economically feasible and what is even more important is their adverse effects on upstream water levels. Also by elimination of natural valley storage they increase downstream peak flows."

The author appreciates that dykes are engineered structures designed to reduce the probability of flooding, but in the circumstances described above the dyke can also be viewed as a flood causal factor in other areas.

4.3.7.3 Dams (VII.c):

a) Dam Failure (VII.c.2):

Many of the major dams in Western Canada are located upstream from heavily populated areas and the sudden collapse of one of these dams could cause extensive flooding. For example, the Mica Dam on the Columbia River in British Columbia has a very deep, 180 kilometre long reservoir behind it. If the Mica Dam was to fail for any reason (earthquake, landslide, etc.) many of the communities located downstream on the Columbia River would be flooded and/or destroyed. While this is a very catastrophic event, the possibility of it occurring is probably fairly low. There is, however, a potential for failure at this and other locations and studies are needed to determine the potential. Once again the author appreciates that dams are often constructed to provide flood protection, but regardless of the cause, that is, precipitation or design flows, major flooding still occurs

downstream if a dam fails. For this reason, dam failures must be considered a potential flood causal factor.

The author was able to find reference to several dam failures in Canada. For example, in 1952 the 20 metre high earth-filled Duncairn Dam on Swift Current Creek (built 1942) partially failed during spring runoff. The heavy runoff required the dam officials to release water from the reservoir at the full capacity of the spillway structure. The downstream end of the spillway dropped 3.05 metres vertically into a pool which had formed from the heavy discharge. The swirling action in this pool apparently caused the spillway basin to undermine, and only emergency measures (sandbagging, etc.) and a timely end of the storm prevented a major dam failure from occurring.

In April 1952, Eastend Reservoir on the Frenchman River failed during the same storm which caused the partial failure of Duncairn Dam. Also in 1952, the Val Marie Dam (earthfill, 1939) failed when spring runoff over-topped the dam as the spillway was unable to handle the discharge. Two other dams, the Fourth Lake Dam (failed 1961) and the Scott Falls Dam (failed 1923) also failed from flood water inundation.

While it was not possible to establish the damages caused by these dam failures, it is enough to realize that they can occur. There are several examples from the United States which further illustrate the possibility of dam failures occurring. In June 1976, the 90 metre high Teton Dam on the Snake River failed. The Edmonton Journal (June 7, 1976, p.2) reported that the dam was controversial from the start because there were claims that the site was located on a fault zone and that the material was too porous to support a dam. The resulting flood caused 11 deaths and hundreds of millions of dollars in property damages. Other recent dam failures in the United States occurred at Johnstown, Pennsylvania in 1977 and at Toccoa Falls in Northeast Georgia.

During the 1964 rain-induced floods in Montana and Southern Alberta (discussed earlier) the failure of Swift Dam on Birch Creek released 36,700 cubic decametres of water and caused the loss of

19 lives. During the same storm the failure of a dam on Two Medicine River in Glacier Park, Montana (June 8) killed 9 people (Warner, 1973, p.20).

It is very difficult to plot the potential occurrence pattern of this flood type aside from presenting a map with all the dam locations on it. This would be a major undertaking, as there are more than 1000 dams in Alberta alone and for this reason the author has elected not to attempt this.

b) Dam Over-topping (VII.c.3):

The possibility of a dam being over-topped by a wave generated within the reservoir should be considered as a dynamic flood causal factor. Because of the steep-walled nature of many of the reservoirs in British Columbia it would be quite possible for a slide to occur which could generate a large surface wave in the reservoir. For example, some of the reservoir walls on McNaughton Lake (behind Mica Dam) are very steep and subject to sliding. If a large enough slide occurred at certain locations in the reservoir, a very large wall of water could run down the Columbia River valley towards Revelstoke. Similarly, if a slide were to occur above the dams on the Kootenay River upstream from Castlegar, several small communities along the river and portions of Castlegar could possibly be flooded. There are also a number of reservoirs located above the city of Vancouver (to the north) which could release a tremendous amount of water onto certain portions of Vancouver and the Lower Mainland if they were over-topped or if failures occurred.

In northern Italy a major wave was created by a landslide shortly after 11 p.m. October 9, 1963 when a portion of Toc Mountain slipped into the reservoir behind Vaiont Dam, the third highest concrete dam in the world. Tufty (1969, p.118) reports that millions of tons of water in waves more than 90 metres high rushed down the valley, killing over 4,000 people. Autumn rains had loosened about 37,500 cubic metres of rock approximately 200 metres above this reservoir. Italian authorities had been aware of the problem and attempted to lower the reservoir which was 6.5 kilometres long,

400 metres wide and 270 metres deep. The Italians had only lowered the reservoir 21 metres when the rock mass slide occurred. The dam held, but approximately 150 million tons of water over-topped the dam destroying the towns of Fae and Langorane and flooding four other villages.

The previous examples are not cited to serve as a scare medium, but only to illustrate how a flood of this type can occur. Because of the steep mountain sides surrounding many of British Columbia's major reservoirs it is a flood causal factor which should be considered.

4.3.8 Land Use Changes In The Watershed (VIII):

Land use changes in the watershed can include a wide range of types and processes, both naturally and unnaturally caused. Forest and wild fires can cause extensive changes in a watershed area, often resulting in increased runoff and erosion and sedimentation problems. Earlier, it was explained how erosion and sedimentation (I.e.1 & 2) can lead to reduced river channel capacities and flooding. Similarly, changes in land use such as forest clearing for arable land can also cause problems. Agricultural practices including down-slope plowing, ridge-and-furrow cultivation and over-grazing by domestic livestock (and ungulates) can speed-up soil erosion and runoff. More obvious changes to the watershed include clear-cutting of forests, urban encroachment into the rural setting, and the introduction of new road networks. These changes in the watershed can increase runoff so that flood waters may accumulate more rapidly. It should be appreciated that most of these changes to the watershed may not individually cause major flood events, but can contribute to increases in flood intensities.

4.3.8.1 Forest and Wild Fires (VIII.a.1&2):

Forest fires or wild fires whether caused by man or by natural elements can increase runoff from a watershed area. In 1980, Manitoba had 1076 forest fires which consumed an area of 769,000 hectares; Alberta had 1338 fires covering a total area of 640,000 hectares; British Columbia had 1763 fires (49,927 hectares); Saskatchewan

had 743 fires (1,495,593 hectares); the Yukon had 150 fires (106,905 hectares); and the Northwest Territories recorded 345 fires which burned over an area of 1,044,286 hectares (Environment Canada, 1980 and Northern Forest Research Center, 1980). The 1980 forest fire figures represent the worst fire year on record for Western Canada.

When a major fire clears the vegetation from a portion of a watershed, runoff and erosion can increase significantly because there is no vegetation to intercept and detain the rain. During spring, snowmelt can occur faster because the shade cover has been removed and the subsequent runoff is quicker, without vegetation to hold it. A number of studies have been conducted in Canada and the United States to determine the impact and yield increases experienced in a watershed after a fire has occurred. The following two case studies were selected because of their relevance to the study area.

Cheng (1980) studied the hydrological changes in Palmer Creek basin (18 square kilometres in area) approximately 3 kilometres west of Salmon Arm, British Columbia, after a severe fire burned over 60% of the watershed Sept. 11 and 12, 1973. The lower portion of the Palmer Creek watershed was completely burned over, while the upper portion was left intact. Cheng used the stream flow characteristics of the upper Salmon River (not burned) which is located in the same drainage basin, as a control and comparison basin. Cheng's results were as follows. After the fire the burned watershed had higher and earlier annual peak flows, an advancement in time of the major snowmelt runoff, and increases in total April-August water yield and monthly yield during the late summer and fall (August-November). These changes are the result of earlier and faster snowmelt and a reduction in evapotranspiration loss from the burned watershed. Over four years (1974-77) the average seasonal water yield increase was 24.0 percent. During the August to November period the average monthly increase in runoff was 37 percent, which indicates that transpiration and interception had been reduced during the growing season. Cheng (1980, p.251) states that peak flows occurred much earlier than in pre-fire years and there was a higher concentration

of runoff in the river channel because the snowmelt period was shorter.

Helvey (1980, pp.627-634) conducted similar research in the Entiat River basin, located northwest of Wenatchee, Washington, which is similar to parts of the Cordillera region in Western Canada. Three watersheds in the basin were used to determine the effects of a major 1970 fire, but one was left in a burned condition to act as a control. Rehabilitation was conducted by grass seeding and log salvaging in the other two watersheds. Helvey (1980, p.631) states that during the seven years following the fire, the utilization of moisture from soil moisture was greatly reduced and runoff rates increased rapidly. The vegetation cover increased over the seven year period, but Helvey estimates that the vegetation would not reduce runoff for at least 50 years until a closed canopy covered the burned area. Helvey (1980, p.632) states that snowmelt occurs earlier because of reduced shading and increased direct shortwave radiation reaching the snow surface. The snowmelt should also have been affected by changes in the wind and snow patterns and other factors. Annual peak flow rates from snowmelt more than doubled after the fire occurred.

The results of these two studies does not necessarily mean that because snow melts faster and earlier from a fire-burned area, this increased runoff will contribute to flooding. This depends also on the altitude of the burned area, the regeneration of the vegetation cover, and the climatic patterns during the recovery period. If a burned area is located so that the snowmelt runoff coincides with the majority of the runoff from the rest of the river basin then it could add to peak flows. In watershed areas where there is widespread burning followed by rapid runoff, localized flooding could result.

The distribution of this flood causal factor in Western Canada coincides with the tree lines in the north and in the south. Tom Weber (personal communication, 1980) of the Water Resources Branch, Department of Natural Resources in Manitoba, suggests that land clearing by forest fire undoubtedly affects runoff and may contribute to flooding in the province. Weber also feels that clearing due

to forest fires in the upland areas of Manitoba and in the northern portion of the province would result in increased runoff, particularly on steeply sloped watersheds. There has not, however, been a program developed to study the extent of this problem in the province of Manitoba.

Schuler and Nyland (personal communication, 1980) of the Forest Resources -- Northern Affairs Program suggest that wild fires do affect large areas throughout the Yukon Territory and can influence runoff significantly. Over the past seventeen years 17,045,024 hectares have burned, which is an average of 1,002,648 hectares per year. The position of Schuler and Nyland's department is that "as wildfire is a natural factor which has a strong influence upon the vegetative patterns in the Yukon, the resulting water regime and flooding can be accepted as natural to the environment." While increased runoff from wildfire may be "natural to the environment" it is still an important flood causal factor and should be considered when planning flood management alternatives.

4.3.8.2 Logging (VIII.b.1&2):

Like forest fires, land cleared by logging generally tends to increase the runoff experienced in a watershed. The increases in runoff which resulted after logging had occurred in several regions of the United States and East Africa are indicated in Table 4.5. There have also been many studies concerning the rate of runoff increase in Western Canada, particularly in Alberta and British Columbia.

Hillman (1974, p.2-3) studied the effects of spring storms on runoff in logged catchments and unlogged catchments in Alberta. A total of 16 catchments, nine logged and seven not logged, were selected near Hinton and Edson in western Alberta. Daily stream flow measurements were collected and hydrographs compiled for the May-June, 1973 period. The hydrographs showed that peak flows from snowmelt occurred earlier on the logged catchments than on the unlogged. Hydrographs from a May 24 to 28 rainstorm illustrated that while the peaks occurred at approximately the same time, flow from the

TABLE 4.5

ANNUAL RUNOFF AS A PERCENTAGE OF ANNUAL PRECIPITATION

Watershed	Location	Not Harvested	Harvested
1. Coweeta 13 (1940)	North Carolina, U.S.A.	43%	64%
2. Coweeta 13 (1962)	North Carolina, U.S.A.	43%	64%
3. Coweeta 3	North Carolina, U.S.A.	33%	40%
4. Coweeta 22	North Carolina, U.S.A.	62%	71%
5. Fernow 1	West Virginia, U.S.A.	38%	47%
6. Fernow 2	West Virginia, U.S.A.	44%	48%
7. Fernow 7	West Virginia, U.S.A.	54%	60%
8. Wagon Wheel Gap	Colorado, U.S.A.	29%	36%
9. Fool Creek	Colorado, U.S.A.	37%	48%
10. Kamakia	East Africa	28%	51%
11. Kenya	East Africa	22%	27%
	$\overline{X}$	39.3	50.5

Source: Northern Forest Research Institute, Edmonton, Alberta. 1981, p.4.

logged areas was greater. Further studies in this and other areas of Alberta by Hillman (1971), Neill (1980), Swanson (1978) and Swanson and Hillman (1977a&b) have had similar results, that is, increased runoff from rain storms on logged areas and heavier and earlier runoff from logged areas during the spring snowmelt period.

Neill (1980, p.70) suggests that it would be possible to increase yields from the Upper Oldman River Basin into southern Alberta by 20 percent. In order to obtain this yield, however, management cutting would also have to be extended to younger tree stands. Neill does suggest that during years of low snowfall, and particularly in sequences of dry years, yield increases would be considerably less or non-existent.

Research by Cheng (1980), Cheng, Black and Willington (1977) and Cheng and Reksten (1980) has provided evidence that logged regions of British Columbia experience the same runoff percentages as those in Alberta. The main difference between the two lies in the greater volumes of runoff which occur in British Columbia (more snow and rain in many areas of the province).

Hillman (1971, p.54) suggests that there is a flood hazard associated with clear-cutting large blocks of forest in Alberta.

> "...in Alberta, snow in the headwaters region is likely to melt before channels are free of ice in the downstream reaches further north. The northward and/or eastward-flowing rivers already show high flood potential. It is reasonable to assume that this situation will be aggravated if large areas of block clearcuts are created in headwater regions of streams in Alberta."

What Hillman is attempting to suggest is that heavy runoff in the upper reaches of a northward flowing river could cause ice jams to form (see section on Ice Jams).

Cheng (1980, p.140) states that, "Another aspect not clearly understood is the impact of logging on peak flows resulting from rain-on-snow events which are often the cause of extreme floods in coastal British Columbia."

Schuler and Nyland (personal communication, 1980) feel that logging operations in the Yukon Territory are so limited when compared to watershed areas that their effect upon runoff and flooding would be insignificant. In the Yukon the majority of logging is confined

to the flood plains and lower benches along major streams and has averaged about 400 hectares per year. Weber (1980, personal communication) claims that there is little logging in the flood-prone areas of Manitoba, and therefore, the effects of logging on runoff are not of particular concern. Weber, however, did not comment on possible flood contributions from logging in the headwaters of the major rivers which eventually flow into Manitoba (e.g. logging in the headwaters of the North and South Saskatchewan River basins). The Northwest Territories, like the Yukon, have no substantial forest industry.

4.3.8.3 Land Drainage (VIII.d):

The primary purpose of land drainage is to remove excess water from the soil in order to improve the agricultural capacity of the land. However, these drainage activities can often have negative hydrologic implications. In many prairie watersheds, large areas of the surface contribute little or no surface runoff to the local streams during heavy precipitation and/or snowmelt periods because much of the water is held in surface depressions. This water usually evaporates or infiltrates into the ground through the summer season. Whiteley (1979, p.15) suggests that if these depressions were filled or if permanent drainage connections were constructed between the depressions and the local stream network, significant increases in the volume of floodwater could result. A volume increase in the runoff could then result in larger discharge peaks being experienced downstream more rapidly than before drainage was conducted.

The magnitude of the increased runoff depends on the scale of drainage in a watershed area. Whiteley (1975, p.46) states that drainage improvement over a small portion of a watershed will usually produce small effects on the peak flow-rates at the outlet of a watershed. When a major proportion of a watershed is improved, higher peaks can be expected from most storms. Found, Hill and Spence (1973, p.47) take this further by suggesting that "the local streamflow patterns may not be seriously affected by the drainage of a single small wetland; but the cumulative effect downstream of the drainage

system may produce serious downstream flooding." Whiteley (1979, p.15) feels that the most conspicuous effects of drainage on downstream flood peaks will be observed when upstream areas, covering a large proportion of the watershed, have drainage "speed-up" while the downstream channel is left in its natural condition. In this case, it is possible that the downstream channel capacity would not be capable of containing the excess runoff during a storm and flooding could result.

The authors previously mentioned make the point that changes in peak flows created by drainage improvement projects are usually most significant for intermediate size storm events. The effects of drainage improvements on very large streamflows is less apparent because heavy runoff would probably have occurred in these areas regardless of drainage works. Banga (1978, p.18), of the Hydrology Branch, Saskatchewan Department of the Environment, provides data indicating that the impact of agricultural drainage upon the flood potential of a basin has a decreasing incremental effect as the magnitude of the flood increases.

> "The percentage increase in flood peak at the City of Moose Jaw due to agricultural drainage can be expressed as ranging from 13 percent +/- 5 percent at the 1 in 2 year flood event to 2.5 percent +/- 5 percent at the 1 in 500 year flood event. Probably the most critical event analysed is the 1:10 flood event since a 1 in 10 year flood represents the approximate bankfull capacity and therefore, the intercept on the probability damage curve through the City of Moose Jaw. The analysis shows that the flood peak potential at the 1 in 10 year event may be expected to increase by 7.9 percent due to the effects of agriculture drainage development at the eight projects upstream."

Land drainage practices in the Carrot River basin, which is located in Saskatchewan (and extends into Manitoba) have also contributed to regional flooding in that area. Collier (1965, p.9) states that the series of floods in the Carrot River basin (1954-57) were caused by excessive precipitation and by the progressive improvement of drainage ditches (part of an agricultural land reclamation program in the region). Serious floods also occurred in 1972 and 1974 when heavy rains fell on unusually deep snow accumulations. During both floods the agricultural land drainage was a contributing factor (Prince Albert Herald, April 25, 1972).

Several other areas in Western Canada are known to experience increased runoff from land drainage. In Alberta, the upper Vermilion and Peace River basins have large areas of drained land and flood intensities have increased as a result. Similarly, much of the change in flood frequency in the Winnipeg area and upstream in the Assiniboine and Red River basins is due to land drainage (Laycock, 1982b). Jenkins (personal communication, 1980) of the Manitoba Department of Agriculture, Land and Water Development Division, suggests that;

> "...changes in land use and drainage in the upper reaches of our watersheds have contributed significantly to the frequency of the smaller floods, i.e., the 5, 10, and 20% floods. It only stands to reason that changing ground cover from forest to annual crop, including fallow will affect water yield. The absence of any kind of headwater retention program as well as the destruction by drainage of significant acreages of natural storage (sloughs, marshes) has contributed to the speed of runoff. How much is difficult to assess."

Laycock (personal communication, January 1981) and Spence (personal interview, June 1981a) suggest that it is very difficult to obtain information on the patterns of land drainage in Western Canada. The information on potential responses to land drainage in Manitoba was provided by Mr. Tom Weber, Director of the Manitoba Water Resources Branch.

4.3.8.4 Contributions To Flooding From Urban Development (VIII.e):

a) Impervious Surfaces and Storm Sewers (VIII.e.1):

Judging from the large amount of literature currently available, storm water runoff from urban centers is becoming recognized as a flood causal factor which can significantly contribute to variations in flood intensity. Increases in impervious urban surfaces such as roofs, roads, commercial and industrial areas, parking lots and airports can effectively reduce the infiltration and evapotranspiration potential in much of the urban setting.

In many urban centers the surface detention storage characteristics have been drastically changed as street runoff and storm sewer systems rapidly remove most of the precipitation. This change in surface runoff patterns has dramatically affected peak flows. Waananen (1969, p.c353) claims that the basin lag time is reduced as an area

becomes urbanized, and the streamflow often is concentrated in sharper, narrower, higher peaks than those for natural runoff. Hollis (1975, p.431) states:

> "...and overland flow can take place readily on the relatively smooth impermeable surfaces. The construction of an urban storm water drainage system invariably increases the drainage density of the catchment and so reduces the time necessary for overland flow to reach a drainage line. Moreover, well-designed and well-graded sewer systems are normally efficient channels in which water velocities are usually in excess of those in natural channels; therefore the drainage from a large area can be more rapidly conducted to the main river channel."

The resulting runoff, therefore, occurs more quickly and flood flows are often higher in the urban catchment than they were prior to urbanization. The existence of storm sewers and impervious surfaces in an urban catchment, therefore, reduces the time required to reach peak runoff after the beginning of a storm to only a few minutes.

McPherson (1974, p.22) suggests that the cumulative effect of increasing surface water volume and localized flood peaks may be to increase the mainstream flooding. Hollis (1975, p.434) supports this when he states:

> "Whilst small frequency floods are increased many times by urbanization, large rare floods that are likely to cause severe damage are not as significantly affected by the construction of urban areas within a catchment area."

In Western Canada almost all urban centers located on a river course can experience this problem. Unfortunately, while many studies of the effects of urbanization on storm runoff have been conducted in the United States, only a limited number of studies have dealt with Canadian urban centers. Taylor (1976, pp.37-38), for example, has studied the effects of urbanization on runoff in Peterbourgh, Ontario. He measured rainfall and snowmelt inputs and runoff discharge during 10 rainstorm events in the spring of 1974. His findings were as follows;

> "For the fall storms the urban basin produced 2.3 times as much direct runoff as the rural basin and the peak discharges for the urban sector were 2.4 times higher on average. The urban-rural contrast was much greater in the spring, however. The urban basin direct runoff volume was 7.5 times that of the rural basin and peaks were 7.1 times higher on average. These changes are serious enough, but it appears that the impact is even greater in the case of spring runoff, a fact which has not been reported elsewhere and which is very important in a region where spring snowmelt generally produces the worst floods of the year."

Similar results have been found by many researchers in the United States (e.g., Chan and Bras, 1975; Hollis, 1975; Leopold, 1968; Martens, 1968; McPherson, 1974; Waananen, 1969).

Laycock (personal communication, March 1982) suggests that in cities in semi-arid and sub-humid areas (e.g. Edmonton, Alberta) the yield increase may be six times that of agricultural areas in the same district. In humid areas, with high agricultural runoff, the yield increase may be well under two times.

b) Urban Encroachment Onto The Flood Plain (VIII.e.2):

In section 4.3.8.1, it was explained how low bridges can deflect flow onto the flood plain during increased runoff periods. A similar situation can occur when urban structures are constructed on the flood plain. Once flood waters have exceeded the capacity of the river channel, and spilled onto the flood plain, urban structures can deflect water further away from the river channel. Water deflection by urbanization can result in larger areas being flooded. Prior to urban encroachment, these areas may not have been flooded during events of equal magnitude. Urbanization on the flood plain could also extend the period of flooding by impeding water returning to the river channel. Environment Canada (1977b) states;

> "Flood damages occur when, through lack of knowledge of the flood problem and disregard of the devastating effects of water, development is allowed on the flood plain. Not only are buildings, bridges and similar structures erected on the flood plain subject to damage themselves, they can obstruct the passage of flood-waters and cause or aggravate flood conditions upstream."

This situation is present in many urban centers in Western Canada. In no city, however, is the potential for this causal factor more apparent than it is in Calgary, Alberta (described in Chapter III). In many of the city districts along the Elbow and Bow Rivers, especially Hillhurst, Sunnyside, Downtown, Glencoe, Elbow Park and Rideau Park, extensive urbanization in the flood plain has created an ideal environment for this type of flooding.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and Conclusions:

It has been the author's contention that the development of a classification of a wide range of factors which can cause and/or contribute to flooding will assist planners when making flood damage reduction decisions. In earlier chapters it has been illustrated that many flood management decisions are often based upon inadequate data bases. Many planners appear to have an incomplete understanding of the many causal factors present in Western Canada, that is, they may not fully appreciate the maximum possible effect of these factors singly and in combination. Therefore, the preceding classification of the causes of flooding was prepared in order to indicate the potential role of each causal factor in flooding in Western Canada. The classification has been designed as an information source which will supplement existing flood forecasting methods, such as flood frequency analysis,by providing the planner with a better understanding of the factors which can cause and/or contribute to flooding in his region. A better understanding of the causal factors in combination with calculated flood frequency analysis estimates and other forecast methods will allow the planner to more accurately select flood damage reduction strategies for particular locations. In Chapter IV, many patterns of occurrence and corresponding management options were presented for the more frequently observed causal factors (e.g., ice jams, air mass anomalies, coastal flooding, snowmelt). Further development of the causal factors in the classification will result in better defined patterns of occurrence, and consequently in more clearly defined management alternatives.

In Chapters III and IV it has been suggested that different flood causal factors have different recurrence frequencies. The presence or absence of a potential flood causal factor during the period of record can cause substantial inaccuracies in the frequency analysis, and can result in somewhat misleading flood return figures. Examples of Hurricane Hazel (1954) in Ontario, the tsunamis generated by the 1964 Alaskan earthquake and the 1976 Big Thompson Canyon

flood are indicative of "exotic" flood events which occurred in regions where an event of such proportions had not been previously experienced during the period of record. These extreme events, while admittedly infrequent, indicate that many causal factors may not be considered when flood frequency patterns are established and flood damage reduction measures are implemented. By having access to a classification of flood causes those involved in the development and administration of flood damage reduction policies would gain further perspectives concerning the causal factors, and in time would learn to intuitively anticipate the extremes associated with each causal factor in a specific region.

In conclusion, the literature review presented in this thesis substantiates the author's contention that there is a need for supplementary techniques to improve existing flood forecasting methods. To this end, a preliminary classification of the factors which can cause and/or contribute to flooding was presented. Potential flood management options for the principle flood causal factors were reviewed to provide an indication of the utility of the classification.

5.2 Limitations of the Study:

It is important to recognize that, as in any study of this complexity, there are a number of limiting factors which have influenced the outcome. Perhaps the most apparent limitation was the shortage of relevant literature and data for many of the less common flood causal factors. As was expected, there was almost unlimited information concerning many aspects of the more frequently observed causal factors (snowmelt, precipitation, etc.), but difficulty was experienced when trying to locate information on causal factors such as interbasin transfers, vegetation constriction of a river channel, various ice jam types and others. The author anticipated this material deficit and attempted to solicit information from many government and private sources. Despite these efforts many gaps were difficult to fill and are apparent in the classification and support discussion in Chapter IV.

The limited information available also affected the selection

and identification of the causal factors. The author made every effort to identify the flood causal factors present in Western Canada, but it is likely that several causal factors were overlooked. It is anticipated that further research and classification development would result in the identification of factors which may be missing.

Data limitations also presented problems when the author was attempting to map the distribution patterns for the more common causal factors (Figures 4.1-4.5). Further research, however, would serve to improve these maps and more defined distribution and occurrence patterns would become apparent. This and the above limitations associated with the apparent data shortage indicates that there is a greater need for further study and appreciation of the many factors which can cause and/or contribute to flooding.

5.3 Recommendations:

While flood frequency analysis will continue to be the basis for most flood management decisions in Canada and abroad, it should be supplemented with better information on the factors which cause and/or contribute to flooding. At present, flood frequency analysis is too often simply an uncritical projection using the streamflow discharge data for the period of record with little reference to the causal factors. Flood damage reduction decisions should be based in part upon a deeper understanding and appreciation of the factors which cause flooding and variations in flood intensity. Awareness of these factors, and of changes in them during the data base period is important, but if due recognition is to be given to these factors it will be necessary to develop a supplementary analysis procedure for use in most regions. This procedure should include a description of each causal factor, the determination of regional distribution patterns for the individual causal factors and frequency-intensity analysis for the flood causal factors, individually and in combination. It is accordingly recommended that an appropriate national body, perhaps starting with the N.S.E.R.C. Associate Committee on Hydrology, investigate and promote development of a classification of flood causal factors and factor combinations. A description of the potential

flood damage reduction options should also be designed for each causal factor. This classification could be used to provide planners with a better appreciation of the causes of flooding when still preliminary. If, after a number of years of additional research, a more detailed and better integrated program can be developed, statistical analysis procedures might be used more effectively and directly in forecasting.

BIBLIOGRAPHY

Alberta. Department of Agriculture. 1971. Lesser Slave Lake Flood Damage Estimation. July. 1971. Prepared by J.L. Knapp. Edmonton, Alberta: Resource Economics Branch. 10 p.

Alberta. Department of Environment. 1971. Brief: Swan Hills Watershed Flood Damage. Edmonton, Alberta. 6 p.

______. 1974. Flood Plain Study Of The North Saskatchewan River Through Edmonton. Prepared by S. Lowe. Edmonton, Alberta: Technical Services Division. 35 p.

______. 1975a. Flood of June 1975 In The Oldman River Basin. Prepared by W. Kuhnke and P. Vos. Edmonton, Alberta: Technical Services Division. 5 p.

______. 1975b. High Mark Coverage: 1975 Flood, Oldman and South Saskatchewan River Basins. Edmonton, Alberta: Technical Services Division.

______. 1975c. Red Deer River Flow Regulation Planning Studies: Main Report. Edmonton, Alberta: Environmental Planning Division. 185 p.

______. 1977. Flood Information Index. Prepared by H. Rickert and G. Foy. Edmonton, Alberta: Technical Services Division, 45 p.

______. 1978a. Cardston Floodplain Study. Prepared by D.N. Outhet. Edmonton, Alberta: Technical Services Division. 16 p.

______. 1978b. Floodplain Study: Oldman River Through Lethbridge. Prepared by G. Beckstead and L. Garner. Edmonton, Alberta: Technical Services Division. 24 p.

______. 1979. Whitecourt Floodplain Study. Prepared by D.N. Outhet and L.B. Penner. Edmonton, Alberta: Technical Services Division. 31 p.

______. 1980. Elbow River Flood Study: Interim Report. Edmonton, Alberta: Planning Division. 26 p.

Alberta. Environment Conservation Authority. 1975. Flood Control and Water Management in the Paddle River Basin: Report and Recommendations. Edmonton, Alberta. 58 p.

Alberta Forest Service. 1977. Flooding In The Clear Hills. ENR Report 31. Edmonton, Alberta. 10 p.

Aldridge, B.N. 1970. "Floods of November 1965 To January 1966 In The Gila River Basin, Arizona and New Mexico, and Adjacent Basins In Arizona." USGS Water-Supply Paper. 1850-c. Washington.

Anderson, D.B. and I.C. Burmeister. 1970. "Floods of March-May 1965 In The Upper Mississippi River Basin." USGS Water-Supply Paper. 1950-a. Washington.

Anderson, Daniel G. 1970. "Effects of Urban Development On Floods In Northern Virginia." USGS Water-Supply Paper. 2001-c. Washington.

Anderson, H.W. 1976. "Fire Effects On Water Supply, Floods and Sedimentation." Proceedings Annual Tall Timber Fire Ecology Conference No. 15. pp. 249-260.

Anderson, William A. 1970. "Tsunami Warning In Cresent City, California and Hilo, Hawaii." The Great Alaska Earthquake of 1964: Human Ecology. National Academy of Science. pp. 116-124.

Antonov, V.S. and Ivanov, V.V. 1972. "Types of Break-up of Rivers in Siberian Arctic and Sub-Arctic Zones." Proceedings: The Role of Snow and Ice in Hydrology. Vol. 1. pp. 541-546.

Barker, Mary L. and Bruce Morgan. 1980. "Shoreline and Floodplain Management In British Columbia and Washington State." Water Problems and Policies. ed. W.R.D. Sewell and Mary L. Barker. Department of Geography: University of Victoria. pp. 49-68.

Barrows, H.K. 1948. Floods Their Hydrology and Control. London, England. pp.1-7.

Benson, Manuel A. 1962a. "Evolution of Methods For Evaluating The Occurrence of Floods." USGS Water-Supply Paper. 1580-a. Washington. 29 p.

______. 1962b. "Factors Influencing the Occurrence of Floods In A Humid Region of Diverse Terrain." USGS Water-Supply Paper. 1980-b. Washington. 64 p.

______. 1968. "Uniform Flood Frequency Estimating Methods For Federal Agencies." Water Resources Research. 4(5). pp. 891-908.

Bobee, B. and J.P. Villeneuve. 1975. "Statistical Distributions: Process and Trends In Flood Frequency Analysis." Canadian Hydrology Symposium - 75; Proceedings. National Research Council of Canada. Associate Committee On Hydrology. Winnipeg. pp. 200-205.

Boner, F.C. and Frank Stermitz. 1967. "Floods of June 1964 In Northwestern Montana." USGS Water-Supply Paper. 1840-b. Washington.

Brater, E.F. and S. Sangal. 1969. "Effects of Urbanization On Peak Flows." Effects of Watershed Changes On Streamflow. ed. W.L. Moore and C.W. Morgan. University of Texas. pp. 201-214.

Brice, H.D. and J.K. Reid. 1975. "Summary of Floods In The United States During 1969." USGS Water-Supply Paper. 2030. Washington. pp. 42-45.

Burton, Ian. 1962. Classification of Types of Agricultural Flood Plain Occupance In The United States. University of Chicago Research Paper 75. 125 p.

Burton, Ian and Robert Kates. 1964. "The Flood Plain and the Seashore: A Comparative Analysis of Hazard-Zone Occurrence." Geographical Review. 54. pp. 366-385.

Burton, I., R.W. Kates and Gilbert F. White. 1978. The Environment As Hazard. New York: Oxford University Press.

Butler, Elmer and Mundorff. 1970. "Floods of December 1966 In Southwestern Utah." USGS Water-Supply Paper. 1870-a. Washington.

Calgary Bow River Study Committee. 1974. Report: 1974. Calgary: Alberta.

Canada. Department of Energy, Mines and Resources and Information Canada. 1974. National Atlas Of Canada. 4th edition. MacMillan Company of Canada; Toronto. pp. 5-6.

Canada. Department of Fisheries and Environment. 1974. New Brunswick Flood, April-May 1973. Technical Bulletin No. 81. Inland Waters Directorate. Halifax, Nova Scotia.

______. 1975. Canada Water Yearbook 1975. Information Canada. Ottawa: Ontario. 232 p.

______. 1976a. Survey and Mapping Procedures For Floodplain Delineation. Ottawa: Department of Environment. 20 p.

______. 1976b. Hydrologic and Hydraulic Procedures For Floodplain Delineation. Ottawa: IWD. 36 p.

______. 1976c. Canada Water Yearbook 1976. Ottawa: Ministry of Supply and Services. 106 p.

______. 1977a. Flood Risk Map: Carman, Manitoba. Ottawa: Ministry of Supply and Services. 21 p.

______. 1977b. Flood Damage In Carman, Manitoba. Ottawa: Ministry of Supplies and Services.

______. 1978a. Canada Water Yearbook 1977-78. Ottawa: Ministry of Supply and Services. 120 p.

______. 1978b. Hydrological Atlas Of Canada. Ottawa: Ministry of Supply and Services. Plates 1-24.

______. 1979. Shore Property Hazards. Ottawa; Ontario. 14 p.

______. 1980a. Historical Streamflow Summary: Alberta to 1979. Ottawa: IWD, Water Survey of Canada.

______. 1980b. Historical Streamflow Summary: British Columbia to 1979. Ottawa: IWD, Water Survey of Canada. 861 p.

______. 1980c. Historical Streamflow Summary: Manitoba to 1979. Ottawa: IWD, Water Survey of Canada. 217 p.

______. 1980d. Historical Streamflow Summary: Saskatchewan to 1979. Ottawa: IWD, Water Survey of Canada.

______. 1980e. Historical Streamflow Summary: Yukon and Northwest Territories to 1979. Ottawa: IWD, Water Survey of Canada. 96 p.

______. 1980f. Historical Water Levels Summary: British Columbia to 1979. Ottawa: Inland Waters Directorate, Water Survey of Canada. 138 p.

______. 1980g. "October Forest Fire Losses Across Canada." News Release Communique. No. 0540. Ottawa, Ontario. 3 p.

______. 1981. Canada Water Year Book 1979-1980: Water Research Edition. Hull; Quebec. 132 p.

______ and New Brunswick. Department of Fisheries and Environment. 1975. Flood Hazard Map Fredericton Area, New Brunswick. Ottawa. 17 p.

Chan Siu-on and R.L. Brass. 1979. "Urban Storm Water Management: Distribution of Flood Volumes." Water Resources Research. 15(2). pp. 371-378.

Changnon, S.A. 1980. "Summer Flooding At Chicago and Possible Relationships To Urban-Increased Heavy Rainfall." Water Resources Bulletin. AWRA. 16(2). pp. 323-326.

Cheng, J.D. 1980. "Hydrologic Effects Of A Severe Forest Fire." Symposium On Watershed Management 1980. Vol. 1. Boise, Idaho, pp. 240-251.

Cheng, J.D. et al. 1975. "The Evolution of Initial Changes In Peak Streamflow Following Logging of a Watershed On the West Coast of Canada." The International Association Of Hydrologic Sciences Symposium Of Tokyo. No. 117. pp. 475-486.

Cheng, J.D., T.A. Black and R.P. Willington. 1977. "The Streamflow Characteristics of A Small, Steep and Forested Watershed In The Coast Mountains of Southwestern B.C." Canadian Hydrological Symposium: 77 Proceedings. pp. 300-310.

Cheng, J.D. and D. Reksten. 1980. "Forestry Impact On Domestic Water Supplies For Small Communities In British Columbia, Canada." International Conference on Water Resources Development. Taipei, Taiwan. pp. 137-149.

Childers, J.M. et al. 1972. "Floods of August 1967 In East-Central Alaska." USGS Water-Supply Paper. 1880-a. Washington.

Chin, E.H. et al. 1975. "The 1973 Mississippi River Basin Flood." USGS Geological Survey: Professional Paper. 937. Washington.

Chorley, R.F. 1969. "The Drainage Basin As The Fundamental Geomorphic Unit." Physical Hydrology. ed. R.J. Chorley. Bungay, England. pp. 37-60.

Chow, Ven Te. 1964. Handbook Of Applied Hydrology. McGraw Hill: N.Y. pp. 1-1 to 29-30.

City of Calgary Planning Department. 1970. The Calgary Plan. Calgary, Alberta.

Clark, E.M. 1980. Personal Communication with Regional Director of Inland Waters Directorate; Pacific and Yukon Region, Environment Canada, October 27, 1980.

Cohos, Evamy and Partners. 1974. The New Town Of Fort McMurray: Ice Jam Flooding. Calgary: Alberta. 60 p.

Collier, E.P. 1965. Flood of 1957 In The Carrot River Basin. Department of Northern Affairs and National Resources, Water Resources Branch. No. 121F. 63 p.

Collins, S.G. and G.K.C. Clarke. 1977. "History and Bathymetry of a Surge-Dammed Lake." Arctic. 30(4). pp. 217-224.

Common, R. 1971. "The 1970 Glen Burn Floods and Their Implications." Irish Geographer. 6(3). pp. 302-306.

Cooley, M.E., B.N. Aldridge and R.C. Euler. 1977. "Effects of the Catastrophic Flood of December 1966, North Rim Area, Eastern Grand Canyon, Arizona." USGS Professional Paper. 980. Washington.

Cruden, D.M. 1976. "Major Rock Slides in the Canadian Rockies." Canadian Geotechnical Journal. Vol. 13. pp. 8-20.

Cruff, R.W. and S.E. Rantz. 1965. "A Comparison of Methods Used In Flood Frequency Studies For Coastal Basins In California." USGS Water-Supply Paper. 1580-e. 56 p.

Daily Colonist. 1979. "Saskatchewan Town Hit By Worst Flooding." April 24, 1979. p.6.

______. 1979. "Flood Threat Rises On Prairie Rivers." April 22, 1979. p. 1.

______. 1979. "Leave Flood Zone, Manitobans Urged." April 25, 1979. pp.1-2.

______. 1979. "Lyon Orders 10,000 To Flee Flooding Area." April 26, 1979. p.1.

______. 1979. "Many Forced From Homes By Rising Island Rivers." December 18, 1979. p.1.

______. 1979. "Port Moody Mud Slides Keeping Residents At Bay." December 18, 1979. p. 25.

Dalrymple, Tate. 1960. "Flood Frequency Analyses: Flood Flow Techniques." USGS Water-Supply Paper. 1543-a. 72 p.

Davies, L.B. et al. 1974. Observations and Report On River Ice Break-up At The Town Of Peace River, Alberta During April 1974. Peace River Ice Task Force. Edmonton, Alberta.

Dean, Willard W. 1971. "Floods of December 1966 In The Kern-Kaweah Area, and Kern and Tulare Counties, California." USGS Water-Supply Paper. 1917-c. Washington.

Dean, Willard W. and J.K. Read. 1975. "Summary of Floods In The United States During 1969." USGS Water-Supply Paper. 2030. Washington. pp. 77-87.

Degtyarev, V.V. et al. 1975. "Investigations of Ice Jams on the Siberian Rivers and Measures Taken to Prevent Them." Third International Symposium On Ice Problems. pp. 223-232.

Dettwiller, J. and S.A. Changnon Jr. 1976. "Possible Urban Effects On Maximum Daily Rainfall at Paris, St. Louis and Chicago." Journal of Applied Meteorology. 15. pp. 517-519.

Doyle, P.F. 1977a. 1977 Break-up and Subsequent Ice Jam at Fort McMurray. Alberta Research Council. Edmonton, Alberta. 25 p.

______. 1977b. Hydrologic and Hydraulic Characteristics of the Athabasca River From Fort McMurray to Embarras. Edmonton, Alberta Research Council. 47 p.

Doyle, P.F. and D.D. Andrews. 1979. 1979 Spring Breakup and Ice Jamming On The Athabasca River Near Fort McMurray. Edmonton, Alberta. Department of the Environment. 40 p.

Dunne, Thomas and Luna B. Leopold. 1978. Water In Environmental Planning. W.H. Freeman and Co.; San Francisco. 818 p.

Dury, G.H. 1969. "Hydraulic Geometry." Introduction to Fluvial Processes. ed. Richard Chorley. London, England. pp. 146-156.

Dybvig, W.L. 1977. The Effects of Agricultural Drainage On Flood Flows at Moose Jaw. Saskatchewan. Department of the Environment Report Number HYD-5-44.

Edmonton Journal. 1974. "Worst Ever Floods Take Big Bite of Crops, Roads, Buildings." April 19, 1974, p.8.

______. 1975. "Regina Mops Up After Storm." June 17, 1975.

______. 1976a. "Flood Threat Appears to Ease In Manitoba." April 12, 1976.

______. 1976b. "Manitoba Flood Situation Stable." April 13, 1976.

______. 1976c. "Flood Waters To Top Dikes in Portage Area." April 10, 1976.

______. 1976d. "6 Dead, 30,000 Homeless As New Idaho Dam Bursts." June 7, 1976, pp. 1-2.

______. 1979a. "No Return Yet in Flooded Manitoba." May 8, 1979.

______. 1979b. "Flood Levels Fell Along Red River." May 12, 1979.

______. 1980a. "Flooding Is Expected." June 19, 1980. p. C2.

______. 1980b. "Mirror Farmland May Be Saved From Flooding." July 16, 1980. p. B19.

Erb, John H. 1965. "Tsunami Warning System." EMO National Digest. 5(3). June 1965. pp. 10-11.

Epsey, William H. and David E. Winslow. 1974. "Urban Flood Frequency Characteristics." Journal of the Hydraulics Division A.S.C.E. Proceedings. 100. 1974. pp. 279-293.

FENCO. 1974. Yukon Flood Study: Report. Prepared for Canada, Department of Indian and Northern Affairs. Whitehorse, Yukon. 140 p.

Fluto, K.A. and P.B. Lemieux. 1975. The 1974 Victoria Day Rainstorm In Winnipeg and Vicinity. Prepared for Environment Canada, Atmospheric Environment Service. Technical Memoranda 824. 12 p.

Foerstel, Hans. 1980. "Mackenzie River Basin Study." Canadian Water Resources Journal. 5(2). 1980. pp. 13-27.

Foster, Harold D. 1979. "Relief Drainage and Natural Hazards." Vancouver Island Land of Contrasts. ed. C.N. Forward. W.G.S. Vol. 17. U. of Victoria: Victoria. 1979. pp. 51-69.

Foster, Harold D. and Vilcho Wuorinen. 1976. "British Columbia's Tsunami Warning System: An Evaluation." Syesis. 9. University of Victoria. 1976. pp. 113-122.

Found, W.C., A.R. Hill, E.S. Spence. 1973. A Study of the Economic and Environmental Impacts of Government-Assisted Land Drainage in Ontario. Select Committee on Land Drainage of the Ontario Legislature, York University: Downsview. 1973. 264 pp.

Fraser River Board. 1956. Interim Report, Investigation Into Measures For Flood Control in the Fraser River Basin. Victoria: Queen's Printer.

______. 1956. Interim Report, Appendix C. Victoria: Queen's Printer.

______. 1963. Final Report of the Fraser River Board on Flood Control and Hydro-Electric Power in the Fraser River Basin. Victoria: Queen's Printer.

Fraser River Joint Advisory Board. 1976. Fraser River Upstream Storage Review Report. Victoria. 184 p.

Furnalle, M.J. 1973. Estimated Damage Around Okanagan Lake During The 1972 Flood. Canada. Department of the Environment. IWD. Pacific Region Water Planning and Management Branch. Vancouver. 14 p.

Gerard, Robert. 1975. "Preliminary Observations of Spring Ice Jams in Alberta." Third International Symposium on Ice Problems. 1975. pp. 261-277.

Gilbert, R. 1972. Drainage of Ice-Dammed Summit Lake, British Columbia. Inland Waters Directorate, Scientific Series No. 20. Ottawa. 17 pp.

Gilstrap, R.C. 1972. "Floods of May 1968 in South Arkansas." USGS Water-Supply Paper. 1970-A. Washington.

Golding, D.L. 1973a. Harvesting Effects on Snowpack Detectable on Marmot Experimental Watershed. Environment Canada. Canadian Forestry Service. Northern Forest Research Center. Forestry Report 2(3):7.

______. 1973b. May-June Streamflow Can Be Reliably Predicted From Snow-Course Data. Environment Canada. Canadian Forestry Service. Northern Forest Research Center. Forestry Report 2(3):4.

______. 1974. "Land Management Practices That Affect Water Yield." In: Golding, D.L. (ed.) Managing Forest Lands for Water. Northern Forest Research Center. Information Report NOR-X-13. pp. 13-32.

Government of Saskatchewan. 1979. Saskatchewan Agriculture: Annual Report. Conservation and Land Improvement Branch. 1979. 31 pp.

Gray, Donald A. 1974. "Safety of Dams - Bureau of Reclamation." Journal of the Hydraulics Division A.S.C.E. Proceedings. 100. 1974. pp. 267-277.

Gray, M. 1964. "Physiographic Characteristics And The Runoff Pattern." Proceedings Of Hydrology Symposium No. 4: Research Watersheds. National Research Council. University of Guelph. pp. 147-164.

Green, G.A.D. 1978. "Annual Large River Flow." Hydrological Atlas of Canada. Ottawa; Ministry of Supply and Services. plate 22.

Grey, B.J. 1977. Spring Break-up At Pipeline Crossings In The Keewatin District: Preliminary Report. Canada, Environmental Social Program, Northern Pipelines. Ottawa. 22 p.

______. 1978. "River Systems Of Canada." Hydrological Atlas Of Canada. Ottawa: Ministry of Supply and Services, plate 20.

Gumbel, E.J. 1966. "Extreme Value Analysis of Hydrologic Data." Proceedings of the Hydrology Sumposium No. 5. NRC. Ottawa. pp. 147-169.

Haan, Charles T. Statistical Methods in Hydrology. Ames, Iowa. 378 p.

Hare, F. Kenneth and Morley K. Thomas. 1974. Climate Canada. University of Toronto. 1974. pp. 103-134.

Harr, R.D. and F.M. McCorison. 1979. "Initial Effects of Clearcut Logging on Size and Timing of peak Flows in a Small Watershed in Western Oregon." Water Resources Research. 15(1), 1979. pp. 90-94.

Harvey, David. 1973. Explanation In Geography. Edward Arnold, London. pp. 326-349.

Helvey, J.D. 1974. "Watershed Behavior After Forest Fire in Washington." Proceedings of the Irrigation and Drainage Division, American Association of Civil Engineers. pp. 403-422.

______. 1980. "Effects Of A North Central Washington Wildfire on Runoff and Sediment Production." Water Resources Bulletin AWRA. 16(4). pp. 627-634.

Hennie, H.H. 1977. "Human Response to Floods - Alberta Experiences." Canadian Hydrology Symposium: 77 Proceedings. Edmonton, Alta. pp. 90-98.

Henock, W.E.S. 1973. "Data (1971) On Height, Frequency of Floods, Ice Jamming and Tree-Ring Studies." Hydrologic Aspects of Northern Pipeline Development. Canada. Department of Environment, Water Resource Branch. Report No. 73-3. Ottawa. pp. 153-177.

Henry, R.F. 1975. Storm Surges: Beaufort Sea Project. Victoria: Department of Environment. Technical Report 19.

Henry, W.K. 1965. "The Ice Jam Floods of the Yukon River." Weatherwise. 18(2) pp. 80-85.

Henz, John F. et al. 1976. "The Big Thompson Flood of 1976 in Colorado." Weatherwise. pp. 278-285.

Hewlett, J.D. and J.D. Helvey. 1970. "Effects of Forest Clear-Cutting on the Storm Hydrograph." Water Resources Research. 6(3). pp. 768-782.

Hewlett, J.E. and A.R. Hibbert. 1967. "Factors Affecting the Response of Small Watersheds to Precipitation in Humid Areas." In International Symposium on Forest Hydrology. pp. 275-290.

Hillman, G.R. 1971. "Probable Hydrological Effects of Clearcutting Large Blocks in Alberta." In: Johnson, H.J. (ed.), Some Implications of Large-Scale Clear-Cutting in Alberta: A Literature Review. Northern Forest Research Center, Information Report NOR-X-6. pp. 44-47.

Howes, D.E. 1981. Terrain Inventory and Geological Hazards: Northern Vancouver Island. British Columbia, Ministry of Environment. Bulletin 5. Victoria. 105 p.

______. 1974. Logged Areas Produce More Water Than Not Logged During Spring Storms. Northern Forest Research Center. Forestry Report. 3(4):2-3.

Hollis, G.E. 1975. "The Effect of Urbanization of Floods of Different Recurrence Intervals." Water Resources Research. Vol. 11(3). pp. 431-435.

Hornal, R.W. 1980. Personal Communication, Director Northern Affairs Program, N.W.T. Region; Yellowknife. August 29, 1980.

Hoyt, W.G. 1936. "Rainfall and Run-Off in the United States." USGC Water-Supply Paper. 772. Washington.

Hoyt, W.G. and Langbein. 1955. Floods. Princeton, N.J. Princeton University Press. 469 p.

Institution of Civil Engineers. 1978. Floods and Reservoir Safety: An Engineering Guide. London, England. 58 p.

International Commission on Large Dams. 1974. Lessons From Dam Incidents. Paris, France.

Jasper, J.N. and R.W. Hornal. 1980. NWT Flood Problems and Management. Personal Communication with Mr. R.W. Hornal Northern Affairs Program, N.W.T. 13 p.

Jenkins, G.C. 1980. Personal Communication with the Chief Agri-Land Section Director, Manitoba Department of Agriculture.

Jensen, Roger. 1977. "Record Storms and Flood Over the Red River Valley, June-July, 1975." Bulletin American Meteorological Society. 59(6). pp. 502-503.

Kennedy, John F. 1975. "Ice Jam Mechanics." Third International Symposium on Ice Problems. pp. 143-164.

Kite, G.W. 1977. Frequency and Risk Analysis in Hydrology. Fort Collins, Colorado. 224 pp.

Klemes, V. 1980. "Aspirations and Realities." Canadian Climate Program Water Workshop. University of Alberta: Edmonton, Alberta. 19 p.

Klohn Leonoff Consultants Ltd. 1976. Feasibility Study, Flood Protection Sundre and Drumheller, Red Deer River. For Alberta Department of the Environment, Planning Division. Calgary, Alberta. 28 p.

Knapp, J.L. 1972. Flood Damage Estimation June 1972 Athabasca, North Saskatchewan, Peace River Basin. Resource Economics Branch, Alberta Department of Agriculture. 12 p.

Knudsen, Tvis N. 1978. "Drainage of an Ice-Dammed Lake in Okstindon, Nordland, Norway." Norsk Geografisk Tidsskrift. 32(2). pp. 55-61.

Kuhnke, W. and I. Barnaby. 1975. June 1975 Flood in the Swan Hills, Lesser Slave Lake Region. Alberta Environment Technical Services Division. Edmonton, Alberta. 12 p.

Kupsch, W.O. 1969. Atlas of the Northwest Territories, Canada. Advisory Commission On The Development of Government In The Northwest Territories. Vol. I-II. map 18. p.75.

Land, Larry F. 1978. "Analysis of Flood Resulting From Toccoa Falls, Georgia, Dam Break." Conference On Flash Floods: Hydrometeorological Aspects. American Meteorological Society. Los Angeles. pp. 127-130.

Laycock, A.H. 1957. Precipitation And Streamflow In Mountain and Foothill Region Of The Saskatchewan River Basin. Prepared for the Prairie Provinces Water Board. Report 6. Regina. 55 p.

______. 1967. Water Deficiency and Surplus Patterns in the Prairie Provinces. Prepared for the Prairie Provinces Water Board, Report No. 13. Regina, Sask. 92 p.

______. 1972. "Diversity of the Physical Landscape." The Prairie Provinces. ed. P.J. Smith, U. of Toronto Press. pp. 1-32.

______. 1976. Water Supplies, Demands and Management In Western Canada. Preliminary report for the Canada West Foundation. 33 p.

______. 1980. Personal Communication, November, 1980.

______. 1981a. Personal Communication, January, 1981.

______. 1981b. Personal Communication, March, 1981.

______. 1981c. Personal Communication, June, 1981.

______. 1982a. Personal Communication, January, 1982.

______. 1982b. Personal Communication, February, 1982.

______. 1982c. Personal Communication, March, 1982.

Lengelle, Jean G. 1976. Anthropogenic Erosion Swan Hills, Alberta. Environment Conservation Authority, Edmonton, Alta. 135 p.

Leopold, L.B. 1968. "Hydrology For Urban Land Planning A Guidebook On The Hydrological Effects of Urban Land Use." USGS Circular. 54. 18 p.

Leopold, Luna B. 1974. Water: A Primer. Freeman, San Francisco. 35 p.

Longley, Richmond W. 1972. The Climate of the Prairie Provinces. (13). Environment Canada, Toronto. 79 p.

Lowe, S. 1974. Floodplain Study of the North Saskatchewan River Through Edmonton. Technical Services Division, Alberta Environment. 35 p.

Maag, H. 1969. Ice-Dammed Lakes And Marginal Drainage On Axel Heiberg Island. Axel Heiberg Island Research Reports. McGill University: Montreal. 147 p.

MacKay, D.K. and J.R. MacKay. 1973a. "Break-up and Ice Jamming on the Mackenzie River, N.W.T." Hydrologic Aspects in Northern Pipeline Development. Environment Canada, Ottawa. pp. 223-232.

______. 1973b. "Locations of Spring Ice Jamming On The Mackenzie River, N.W.T." Hydrologic Aspects Of Northern Pipeline Development. Canada. Department of Environment, Water Resources Branch. Report No. 73-3. Ottawa. pp. 233-257.

MacKay, D.K., S. Fogarasi and M. Spitzer. 1973. "Documentation Of An Extreme Summer Storm In The Mackenzie Mountains, Northwest Territories." Hydrologic Aspects Of Northern Pipeline Development. Environment Canada, Water Resources Branch. Report No. 73-3. Ottawa. pp. 195-218.

MacKay, J. Ross. 1960. "Freeze-Up And Break-Up Of The Lower Mackenzie River, Northwest Territories." Proceedings of the First International Symposium On Arctic Geology. Vol. II. University of Toronto Press. pp. 1119-1134.

Mackenzie, Frank B. 1981. "Are Municipalities Net Producers Rather Than Net Consumers Of Water." Canadian Water Resources Conference. Banff, Alberta.

Magura, L.M. and Wood, D.E. 1980. "Flood Hazard Identification and Flood Plain Management On Alluvial Fans." Water Resources Bulletin. AWRA. 16(1). pp. 56-62.

Marcus, M. 1960. "Periodic Drainage Of Glacier-Dammed Tulsequah Lake, British Columbia." Geographical Review. 50(1). pp. 89-106.

Martins, L.A. 1968. "Flood Inundation And Effects Of Urbanization In Metropolitan Charlotte, N.C." Geological Survey Water-Supply Paper 1591-c. Washington, 60 p.

Matthews, W.H. 1965. "Two Self-Dumping Ice-Dammed Lakes in British Columbia." Geographical Review. 55(1). pp. 46-52.

Matthai, H.F. 1969. "Floods of June 1965 in South Platte River Basin, Colorado." USGS Water-Supply Paper. 1850-B. Washington.

McCuen, Richard H. 1980. "A Decision Theory Approach to Earth Dam Classification." Water Resources Bulletin. AWRA. 16(3). pp. 546-549.

McMann, Donald. 1979. "Preparing for the Unpredictable Flooding Caused by Ice-Jams is a Fort McMurray Headache." Environment News. Vol. 2:3. pp. 10-12.

McPherson, M.B. 1974. Hydrological Effects Of Urbanization. Prepared by The Subgroup On The Effects of Urbanization On The Hydrological Environment. International Hydrological Decade. The Unesco Press. Paris. 280 p.

Miles, Michael J. 1981. Regional Hydrology of the Northeast Coal Study Area. Prepared for the Environment and Land Use Sub-Committee on Northeast Coal Development. British Columbia Ministry of Environment, APD-3. Victoria. 78 p.

Montreal Engineering Company Ltd. 1968. Floodplain of Bow River in the City of Calgary. Vol. 1 and 11. Water Resources Division. Alberta Department of Agriculture. Water Resources Division.

______. 1969. St. Georges Island Flood Protection. Calgary, Alberta. p. 9.

Montreal Star. 1972. "Thompson River Flood Ebbs." June 5, 1972.

Moore, W.G. 1949. A Dictionary of Geography. Aylesbury, Britian. 234 p.

Mudry, N., Reynolds, P.J. and Rosenberg, H.B. 1981. "Post-Project Evaluation of the Red and Assiniboine River Flood Control Project." 11th International Commission on Irrigation and Drainage. Grenoble, France. 36 p.

National Research Council, Subcommittee On Hydrology. 1965. Proceedings Of Hydrology Symposium No. 4: Research Watersheds. University of Guelph. 321 p.

Nash, J.E. and J. Amorocho. 1966. "The Accuracy of the Prediction of Floods of High Return Period." Water Resources Research. 2(2). pp. 191-198.

Neill, C.R. et al. 1970. Selected Characteristics of Streamflow in Alberta. for the Research Council of Alberta Surface Engineering and Surface Hydrology Report 70-1. Edmonton, Alberta. 54 pp.

Neill, Charles R. 1980. "Forest Management for Increased Water Yield - How Useful in Southern Alberta?" Canadian Water Resources Journal. 5(1). pp. 56-75.

Nemanishen, W. and L.S. Meeres. 1980. Lesser Slave Lake Flood Study. Water Survey of Canada Atmospheric Environment Services. IWD, Environment Canada. 127 pp.

Newson, Malcolm D. 1974. Flooding And Flood Hazard In The United Kingdom. Oxford University Press. 58 p.

O'Connell, D.J. and J.O. Rostvedt. 1972. "Floods of June and August in Wyoming." Floods of 1968 in the United States. USGS Water-Supply Paper. 1970-B. Washington. pp. 37-40.

Orecklin, Mel. 1980. Personal Communication, Hydrologist, Northern Affairs Program, Canada. Yukon Territory. September 25, 1980.

Osborn, Gerald et al. 1975. Homeowner's Guide to Geologic and Hydrologic Hazards in Calgary. University of Calgary. pp. 34-58.

Owen, J.A. and D.R. Nancarrow. 1977. "Flooding in the City of Calgary." Canadian Hydrology Symposium: 77 Proceedings. Edmonton, Alta. pp. 100-110.

Pelech, H. 1980. Personal Communication with the Senior Planning and Design Engineer, Saskatchewan Agriculture. August 22, 1980.

Pentland, R.L. and D.R. Cuthbert. 1973. "Multisite Daily Flow Generator." Water Resources Research. 9(2). pp. 470-473.

Piper, R.F. and P.W. Ward. 1929. The Fields and Methods of Knowledge. New York.

Pollock, D.M. 1975. An Index to Storm Rainfall in Canada. Environment Canada, Downsview, Ont. CL1-1-75.

Prince Albert Herald. 1972a. "Runoff Endangers Farmland Roads in Several Areas." April 25, 1972.

______. 1972b. "Flood-Swollen Carrot River Swamps Land." April 26, 1972.

______. 1972c. "Carrot River Flood Waters Appear To Be Past Peak." April 17, 1972.

Putnam, D.F. and R.G. Putnam. 1970. Canada: A Regional Analysis. Dent & Sons: Canada. 390 p.

Qu-Appelle Basin Study Board. 1974. Wascana Creek Flood Study. Regina, Sask. 15 p.

Rannie, W.F. 1980. "The Red River Flood Control System and Recent Flood Events." Water Resources Bulletin. AWRA. 16(2). pp. 207-214.

Reich, B.M. 1973. "Log Pearson Type III and Gumbel Analysis of Floods." Proceedings of the Second International Symposium in Hydrology, Floods and Droughts. Water Resources Publications, Fort Collins, Colorado. pp. 291-303.

Reimnitz, E. and Maurer, D.K. 1979. "Effects Of Storm Surges On The Beaufort Sea Coast, Northern Alaska." Arctic. 32(4). pp. 329-344.

Richardson, E.C. 1912. Classification: Theoretical and Practical. New York.

Rodda, John C. 1969. "The Flood Hydrograph." Introduction to Physical Hydrology. ed. Richard J. Chorley. Methuen; London. pp. 162-175.

Rodda, R.C., R.A. Downing and F.M. Law. 1976. Systematic Hydrology. Newnes-Butterworths; London. 399 p.

Roeske, R.H., M.E. Cooley, and B.N. Aldridge. 1978. "Floods of September 1970 in Arizona, Utah, Colorado and New Mexico." USGS Water-Supply Paper. 2052. Washington.

Rosenberg, H.B. 1980. Personal communication with the Chief of Socio-Economics Division, Water Planning and Management Branch, IWD, Environment Canada. July 29.

Rostvedt, J.O. et al. 1968a "Summary of Floods in the United States During 1962. USGS Water-Supply Paper. 1820. Washington.

______. 1968b. "Summary of Floods in the United States During 1963." USGS Water-Supply Paper. 1830-B. Washington.

______. 1970. "Summary of Floods in the United States During 1965." USGS Water-Supply Paper. 1850-E. Washington.

______. 1972. "Summary of Floods in the United States During 1967." USGS Water-Supply Paper. 1880-C. Washington.

Rothacher, J. 1970. "Increases in Water Yield Following Clear Cut Logging in the Pacific Northwest." Water Resources Research. 6(2). pp. 653-658.

______. 1973. "Does Harvest in West Slope Douglas Fir Increase Peak Flow in Small Forest Streams?" U.S. Forest Research Paper. PNW-163. 13 p.

Russell, Thomas. 1906. Meteorology and River Flood Predictions in the United States. London. pp. 198-212.

Sadler, Barry. 1980. "The Regulation of the Red Deer River: Conflict and Choice." in Water Problems and Policies.

Saint John River Basin Board. 1972. Floods In The Saint John River Basin. Prepared by Environment Canada, IWD. Report No. S3. Ottawa. 14 p.

______. 1975. A Plan For Water Management In The Saint John River Basin: Final Report. Fredericton. 262 p. W.R.D. Sewell and M.L. Barker, Department of Geography, University of Victoria. pp. 91-109.

Sangal, S. and E.F. Bater. 1969. "Effects of Urbanization on Peak Flows." Effects of Watershed Changes on Streamflow. eds. W.L. Moore and C.W. Morgan. University of Texas Press. pp. 201-215.

Santos, A. 1970. "The Statistical Treatment of Flood Flows." Water Power. 22(2). pp. 63-67.

Saskatchewan Department of Agriculture. 1980a. Channel Clearing Policy for Rural Municipalities. Conservation and Land Improvement Branch. 3 p.

______. 1980b. Flood Control Policy for Urban Centers. Conservation and Land Improvement Branch. 3 p.

______. 1980c. Water Control Policy. Saskatchewan Agriculture. 4 p.

Saskatchewan Department of the Environment. 1978. Flood Peak Potential at Moose Jaw. Prepared by A.B. Banga. Regina, Sask. Hydrology Branch Report No. HYD-5-47. 60 p.

Schroeder, E.E. et al. 1974. "Floods of September-October 1967 in South Texas and Northeastern Mexico." USGS Water-Supply Paper. 1880-B. Washington. 120 p.

Shuler, A. and E. Nyland. 1980. Personal Communication. August 15, 1980.

Sewell, W.R. Derrick. 1965. Water Management and Floods in the Fraser River Basin. University of Chicago. No. 100.

Simmons, G.E. 1979. Personal Interview with Assistant Deputy Minister of the Environment, British Columbia. April 16, 1979.

______. 1980a. Personal Communication. September 1.

______. 1980b. "Approaches to Flood Control on the Fraser River." Water Problems and Policies. ed. W.R.D. Sewell and M.C. Barker. Department of Geography. University of Victoria. pp. 35-45.

______. 1982. Personal Interview, April 1.

Smith, A.G. 1975. Flood of June 1971 Fort Nelson and Muskwa Rivers. Technical Bulletin No. 85. Environment Canada. IWD. Vancouver, B.C. 49 p.

Smith, D.I. and P. Stopp. 1978. The River Basin. Cambridge University Press, Cambridge. pp. 69-84.

Smith, H.F. 1969. "Effect of Urban Development on Flood Discharges - Current Knowledge and Future Needs." Journal of the Hydraulics Division. ASCE. 95 (HY1) Proc. Paper 6355. pp. 287-309.

Sniatyski, G. 1979. "Down By The Riverside." Environment Views. 2(3). pp. 16-17.

Snipes, R.J. 1974. "Floods of June 1965 in Arkansas River Basin, Colorado, Kansas and New Mexico." USGS Water-Supply Paper. 1850-D. Washington.

Spence, E.S. 1973. "Theoretical Frequency Distributions for the Analysis of Plains Streamflow." Canadian Journal of Earth Sciences. 10, pp. 130-139.

______. 1981. Personal Communication, June 1981.

STAR - Phoenix. 1972. "Rampaging River." May 1, 1972.

Staite, Margaret Jane. 1979. Flood Plain Management in the Drumheller Valley: Alternative Land Use Policies. University of Alberta M.A. Thesis (Unpublished). 278 pp.

Stolte, W.J. and G.R. Dumontier. 1977. Flood Frequency for Mountainous and Prairie Streams. Water Sciences Group, Department of Civil Engineering. University of Saskatchewan. Saskatoon, Sask. Research Report H4-77-03. 81 p.

Stone, K.H. 1963a. "The Annual Emptying Of Lake George." Arctic. 16. pp. 26-39.

______. 1963b. "Alaskan Ice-Dammed Lakes." Annals of the Association of American Geographers. 53(3). pp. 332-349.

Swanson, Robert H. 1978. Water Management Aspects of Forestry Operations in Alberta. Northern Forest Research Center. Edmonton, Alberta. 14 p.

Swanson, Robert H. and G.R. Hillman. 1977a. Predicted Increased Water Yield From Clear-Cutting Verified in West-Central Alberta. Fisheries and Environment Canada. Canada Forest Service. Northern Forest Research Center. Edmonton, Alta. Information Report NOR-X-198.

______. 1977b. "Effect of Large-Scale Clear-Cutting on Water Yield in Western Alberta." Alberta Watershed Research Program: Symposium Proceedings: 1977. Northern Forest Research Center. Edmonton, Alberta. pp. 256-271.

Tada, Fumio and M. Ohya. 1959. "The Flood-Type and the Classification of the Topography." Proceedings of the IGU Regional Conference In Japan 1957. Tokyo. pp. 192-196.

Task Committee on Hydromechanics of Ice of the Committee on Hydromechanics of the Hydraulics Division. 1974. "River Ice Problems: A State-Of-The-Art Survey and Assessment of Research Needs." ASCE Proceedings. 100. pp. 1-15.

Taylor, C.H. 1975. "Effects of Suburban Development On Streamflow In A Small Basin In Peterborough, Ontario." Canadian Hydrology Symposium - 75: Proceedings. National Research Council. Associate Committee On Hydrology. Winnipeg. pp. 746-750.

______. 1976. "A Study In Urban Hydrology: Peterborough, Ontario." Proceedings of Cagont '76. Ontario Division, Canadian Association of Geographers. Trent University. pp. 36-37.

The Gazette. 1972. "North B.C. Interior Flood Damage High." June 5, 1972.

Thomas, Morley K. 1953. Climatological Atlas of Canada. Meteorological Division. Department of Transport. Ottawa, Ontario.

Thompson, W.C. 1976. Three Early Severe Flood Producing Storms in Alberta. Environment Canada. Downsview, Ont. Technical Memoranda TEC 827. 21 p.

Times-Colonist. 1980. "Flood Aid Plotted as Roads Reopen." December 29, 1980. p. 1.

Trewartha, Glen T. 1968. An Introduction to Climate. University of Wisconsin. Fourth Ed. 408 p.

Tufty, Barbara. 1968. 1001 Questions and Answers About Earthquakes, Avalanches, Floods and Other Natural Disasters. General Pub. Toronto. 350 p.

Underhill, A.G. 1962. Report: Potential Flooding Problems in the Area Along the South Side of the Bow River and West of the Mewata Bridge. Calgary, Alberta. 58 p.

Vancouver Sun. 1978. "Storm Fury Moves East as Edmonton Cleans Up." July 12, 1978. p. A14.

Vershuren, J.P. and L. Woitiw. 1980. Estimate of the Maximum Probable Precipitation for Alberta River Basins. University of Alberta. For the Alberta Department of Environment. 307 p.

Victoria Times. 1979. "Prairies Reeling From Spring Floods." April 23, 1979. p. A1.

______. 1979. "Floods of the Century Feared, S. Manitoba." April 25, 1979. p. 1.

______. 1979. "Troops Move on Floods." April 26, 1979. p. 1-2.

______. "Rains, Slides Wreak Havoc." Dec. 17, 1979. p. 1.

Waananen, A.O. 1961. "Hydrologic Effects of Urban Growth; Some Characteristics of Urban Runoff." USGS Professional Paper 575-D. Washington. pp. C353-c356.

Waananen, A.O. et al. 1971. "Floods Of December 1964 and January 1965 In The Far Western States." USGS Water-Supply Paper 1866-A. Washington. 64 p.

Walesh, Stuart G. and Randolph M. Videkovich. 1978. "Urbanization: Hydrologic - Hydraulic - Damage Effects." Journal of the Hydraulics Division. 104. pp. 241-255.

Ward, R.C. 1975. Principles of Hydrology. 2nd. edition. McGraw-Hill, England. 367 p.

Warner, L.A. 1973. Flood of June 1964 in the Oldman and Milk River Basins, Alberta. Canada Department of the Environment. IWD Ottawa, Ontario. Technical Bulletin. No. 73. 89 p.

Warner, L.A. and W.C. Thompson. 1974. Flood of June 1972 in the Southern Peace (Smokey River) Basin Alberta. Technical Bulletin 87. IWD Environment Canada, Calgary, Alberta. 51 p.

Warwick, W.J. 1978. "Historical Aspects of Urban Drainage in Ontario." Canadian Water Resources Journal. 3(2). pp. 25-30.

Watt, W.E. 1975. "Hydrologic Effects Of Urban Development." Canadian Hydrology Symposium - 75: Proceedings. National Research Council of Canada. Associate Committee on Hydrology. Winnipeg. pp. 709-717.

Weber, T.E. 1980. Personal Communication. Director, Manitoba Water Resources Branch. September 12, 1980.

White, G.F. ed. 1961. Papers on Flood Problems. Research Paper #70. University of Chicago. Department of Geography.

______. 1964. Choice of Adjustments to Floods. Research Paper #93. University of Chicago. 150 p.

Whiteley, H.R. 1975. "Does Drainage Add to Flood Peaks?" Proceedings of the Drainage Engineering Conference. English Technical Publication 126-132. School of Engineering. University of Guelph. pp. 40-46.

______. 1979. "Hydrologic Implications of Land Drainage." Canadian Water Resources Journal. 4(2). pp. 12-19.

Whyte, G.H. 1917. "Floods in Alberta and Saskatchewan in June and July 1915." Report on Hydrometric Surveys for the Calendar Year 1915. Ottawa, Ontario. pp. 543-577.

Wight, J.B. 1973. Aspects of Evaporation and Evapo-transpiration in the Water Balance of Baker Creek Basin. University of Alberta. Unpublished M.Sc. Thesis, Department of Geography. 329 p.

Wilford, D.J. 1976. Peak Flows in the Quesnel River: Their Difference on Peak Flows in the Fraser River and the Influence of Forest Harvesting. Received from B.C. Ministry of the Environment. 15 p.

Williams, G.P. 1970. "Correlating Freeze-up and Break-up with Weather Conditions." Weather and Climate. ed. J.G. Nelson and M.J. Chambers. pp. 281-301.

Wolf, P.O. 1966. "Comparison of Methods of Flood Estimation." River Flood Hydrology. The Institution of Civil Engineers. London. pp. 1-38.

Wood, W.A. 1972. "Steele Glacier, 1935-1968." Icefield Ranges Research Project, Scientific Results Vol. 3. Eds. V.C. Brushnell and R.H. Ragle. New York: American Geographical Society. Montreal: Arctic Institute of North America. pp. 1-8.

Young, G.J. 1977. "Glacier Outburst Floods." Canadian Hydrology Symposium: 77 Proceedings. Edmonton, Alberta. pp. 1-12.

Zoltai, S.C. 1973. "Vegetation, Surficial Deposits and Permafrost Relationships In The Hudson Bay Lowlands." Proceedings of the Symposium on the Physical Environment of the Hudson Bay Lowlands. University of Guelph. Guelph, Ontario. pp. 17-34.

APPENDIX I: CHARACTERISTICS OF RIVERS IN WESTERN CANADA

DRAINAGE SYSTEM – HYDROMETRIC STATION	DRAINAGE AREA (Km^2)	MAXIMUM DAILY DISCHARGE (m^3/s)	MINIMUM DAILY DISCHARGE (m^3/s)	MEAN TOTAL DISCHARGE (dam^3)	MAXIMUM MONTHLY MEAN DISCHARGE (m^3/s)	MINIMUM MONTHLY MEAN DISCHARGE (m^3/s)	PERIOD OF RECORD
A. Arctic Drainage:							
1. MacKenzie River at Norman Wells	1 570 000	30 300 (1975)	1 950 (1979)	270 000 000	16 900 (Jun)	2 970 (Mar)	1943–79
2. Back River below Deep Rose Lake	98 200	5 150 (1969)	2.89 (1967)	15 000	2 070 (Jul)	34 (Apr)	1962–79
3. Peel River above Fort McPherson	70 700	10 600 (1975)	45.9 (1972)	24 500 000	2 850 (Jun)	67.7 (Mar)	1969–79
4. Liard River at Fort Liard	222 000	16 500 (1963)	172 (1972)	63 200 000	6 430 (Jun)	307 (Mar)	1958–79
5. Peace River at Peace River	186 000	14 100 (1963)	149 (1961)	56 200 000	5 270 (Jun)	559 (Feb)	1915–79
6. Athabasca River below Fort McMurray	133 000	4 700 (1971)	104 (1970)	22 100 000	1 470 (Jul)	169 (Feb)	1957–79
B. Hudson Bay Drainage:							
1. Thelon River above Baker Lake	154 000	3 510 (1978)	161 (1974)	24 800 000	2 110 (Jun)	246 (Mar)	1973–79
2. Kazan River above Dazan Falls	72 300	1 930 (1975)	18.3 (1976)	13 000 000	1 170 (Jul)	73.4 (Mar)	1965–79
3. Churchill River above Granville Falls	228 000	1 700 (1949)	501 (1971)	26 800 000	977 (Jul)	726 (Apr)	1949–79

DRAINAGE SYSTEM – HYDROMETRIC STATION	DRAINAGE AREA (km^2)	MAXIMUM DAILY DISCHARGE (m^3/s)	MINIMUM DAILY DISCHARGE (m^3/s)	MEAN TOTAL DISCHARGE (dam^3)	MAXIMUM MONTHLY MEAN DISCHARGE (m^3/s)	MINIMUM MONTHLY MEAN DISCHARGE (m^3/s)	PERIOD OF RECORD
4. Nelson River at Kelsey, Manitoba	1 010 000	4 980 (1966)	4.9 (1977)	75 000 000	3 030 (Jul)	1 890 (Feb)	1960–79
5. Winnipeg River at Slave Falls	126 000	2 800 (1954)	51 (1977)	26 600 000	1 040 (Jun,Jul)	741 (Mar)	1907–79
6. Red River at Emerson	104 000	2 670 (1950)	0.025 (1937)	2 970 000	351 (Apr)	19.9 (Feb)	1912–79
7. Assiniboine River at Headingley	153 000	614 (1915)	0.566 (1936)	1 530 000	155 (May)	9.17 (Feb)	1913–79
8. Qu'Appelle River at Tantallon	49 200	240 (1955)	0 (1931)	244 000	19.9 (May)	1.77 (Feb)	1919–74
9. Souris River near Sherwood	22 400	388 (1976)	0 (1930)	129 000	22.6 (Apr)	0.095 (Feb)	1930–79
10. North Saskatchewan River at Prince Albert	131 000	5 300 (1915)	11.2 (1935)	7 670 000	587 (Jul)	48 (Jan)	1910–79
11. North Saskatchewan River at Edmonton	28 000	4 640 (1915)	6.23 (1940)	6 800 000	543 (Jun)	49 (Feb)	1911–79
12. South Saskatchewan River at Saskatoon	141 000	3 940 (1953)	14.2 (1936)	8 470 000	693 (Jun)	114 (Feb)	1911–79
13. Oldman River near Lethbridge	17 000	2 890 (1953)	2.61 (1977)	2 860 000	350 (Jun)	22.4 (Jan)	1911–79

DRAINAGE SYSTEM – HYDROMETRIC STATION	DRAINAGE AREA (km^2)	MAXIMUM DAILY DISCHARGE (m^3/s)	MINIMUM DAILY DISCHARGE (m^3/s)	MEAN TOTAL DISCHARGE (dam^3)	MAXIMUM MONTHLY MEAN DISCHARGE (m^3/s)	MINIMUM MONTHLY MEAN DISCHARGE (m^3/s)	PERIOD OF RECORD
14. Bow River at Calgary	7 870	*1 160 (1932)	3.48 (1930)	2 910 000	243 (Jun)	43 (Feb)	1908–79
15. Red Deer River at Red Deer	11 600	1 590 (1915)	1.81 (1922)	1 550 000	133 (Jun)	8.61 (Jan)	1912–79
C. PACIFIC DRAINAGE:							
1. Fraser River at Hope	217 000	15 200 (1948)	340 (1916)	86 200 000	7 070 (Jun)	821 (Mar)	1912–79
2. Somass River near Alberni	191	1 149 (1961)	22 (1958)	4 982 800	210 (Dec)	46 (Aug)	1957–79
3. Columbia River at U.S. Border	155 000	15 500 (1948)	578 (1945)	90 000 000	7 430 (Jun)	1 370 (Feb)	1938–79
4. Kootenay River at Porthill (Washington)	35 500	3 540 (1948)	39 (1936)	14 300 000	1 330 (Jun)	177 (Jan)	1928–79
5. Skeena at Usk	42 200	9 340 (1948)	51.8 (1950)	29 000 000	2 840 (Jun)	145 (Mar)	1928–79
6. Cowichan River at Lake Cowichan	596	326 (1968)	0.4 (1944)	1 420 000	91.5 (Dec)	7.5 (Aug)	1913–79

*There was Maximum Instantaneous Discharge of 2,270 in 1897.

DRAINAGE SYSTEM – HYDROMETRIC STATION	DRAINAGE AREA (km^2)	MAXIMUM DAILY DISCHARGE (m^3/s)	MINIMUM DAILY DISCHARGE (m^3/s)	MEAN TOTAL DISCHARGE (dam^3)	MAXIMUM MONTHLY MEAN DISCHARGE (m^3/s)	MINIMUM MONTHLY MEAN DISCHARGE (m^3/s)	PERIOD OF RECORD
7. Yukon River at Dawson	264 000	14 900 (1964)	180 (1951)	70 000 000	5 920 (Jun)	423 (Mar)	1945–79
8. Pelly River above Pelly Crossing	49 000	4 300 (1957)	28.3 (1974)	12 300 000	1 440 (Jun)	47.7 (Mar)	1952–79
D. GULF OF MEXICO DRAINAGE:							
1. Milk River at Milk River	2 720	207 (1975)	0 (1922)	281 000	18.8 (Jun)	0.9 (Jan)	1909–79

Source: Canada. Department of Fisheries and Environment (1980a-F).

APPENDIX II: GLOSSARY OF TERMS

Channel Detention Storage	Volume of water which can be temporarily stored in channels during flood periods.
Confluence	Joining, or place of junction, of two or more streams.
Crest	Top of a dam, levee, spillway or weir to which water must rise before passing over the structure.
Depression Storage	Volume of water which is required to fill small natural depressions to their overflow levels.
Detention Storage	That part of the precipitation which is temporarily stored en route to the stream system, during or shortly after rainfall. Includes surface and channel detention but does not include depression storage.
Discharge, Mean Monthly	Arithmetic mean of all the individual monthly mean discharges for the months of that name in a period of record.
Discharge, Peak	Maximum instantaneous rate of discharge for a given period.
Drainage Basin	Whole area having a common outlet for its surface runoff.
Flash Flood	Flood of relatively short duration with a relatively high peak discharge.
Flood	Rise, usually brief, in the water level in a stream to a peak from which the water level recedes at a slower rate.
Flood, Annual	Highest daily peak discharge in a water year.
Flood Flow	Volume of water flowing across a section of a stream during a flood per unit time.
Flood Forecasting	Prediction of stage, discharge, time of occurrence, and duration of a flood, especially of a peak discharge at a specific point on a stream,

resulting from precipitation and/or snowmelt.

Flood Frequency — Number of times a flood above a given discharge or stage is likely to occur over a given number of years.

Flood Probability — Probability of a flood of a given stage being equalled or exceeded in a given year.

Flooding — Overflowing by water of the normal confines of a stream or other body of water, or accumulation of water by drainage over areas which are not normally submerged.

Frequency Analysis — Procedure involved in interpreting a past record of hydrological events in terms of future probabilities of occurrence, e.g. Estimates of frequencies of floods.

Infiltration — Flow of water from the soil surface into the soil.

Infiltration Capacity — Maximum rate at which water can be absorbed by a given soil per unit surface under given conditions.

Lag-time — Time between center of mass of rainfall to center of mass of runoff, onto the peak of runoff.

Moisture, Antecedent Soil — Parameter expressing soil-moisture conditions at the start of a rain storm.

Storm Runoff — That portion of the total runoff from storm rainfall which reaches the point of measurement within a relatively short period of time subsequent to the occurrence of rain. It essentially excludes the base flow.

Storm Surge — Elevation of sea or estuary level above the expected tide or flood height caused by the passage of a low pressure center.

Water Balance	Balance of input and output of water within a given defined hydrological area such as a basin, lake, etc., taking into account net changes of storage.
Water Yield	Total runoff from a drainage basin through surface channel and aquifers.

Source: United Nations Educational Scientific and Cultural Organization. 1974. International Glossary of Hydrology. World Meteorological Organization, No. 385. Geneva, Switzerland. 393 p.